Experimental Techniques Lecture 2

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Fifth CERN-Fermilab Hadron Collider Physics Summer School

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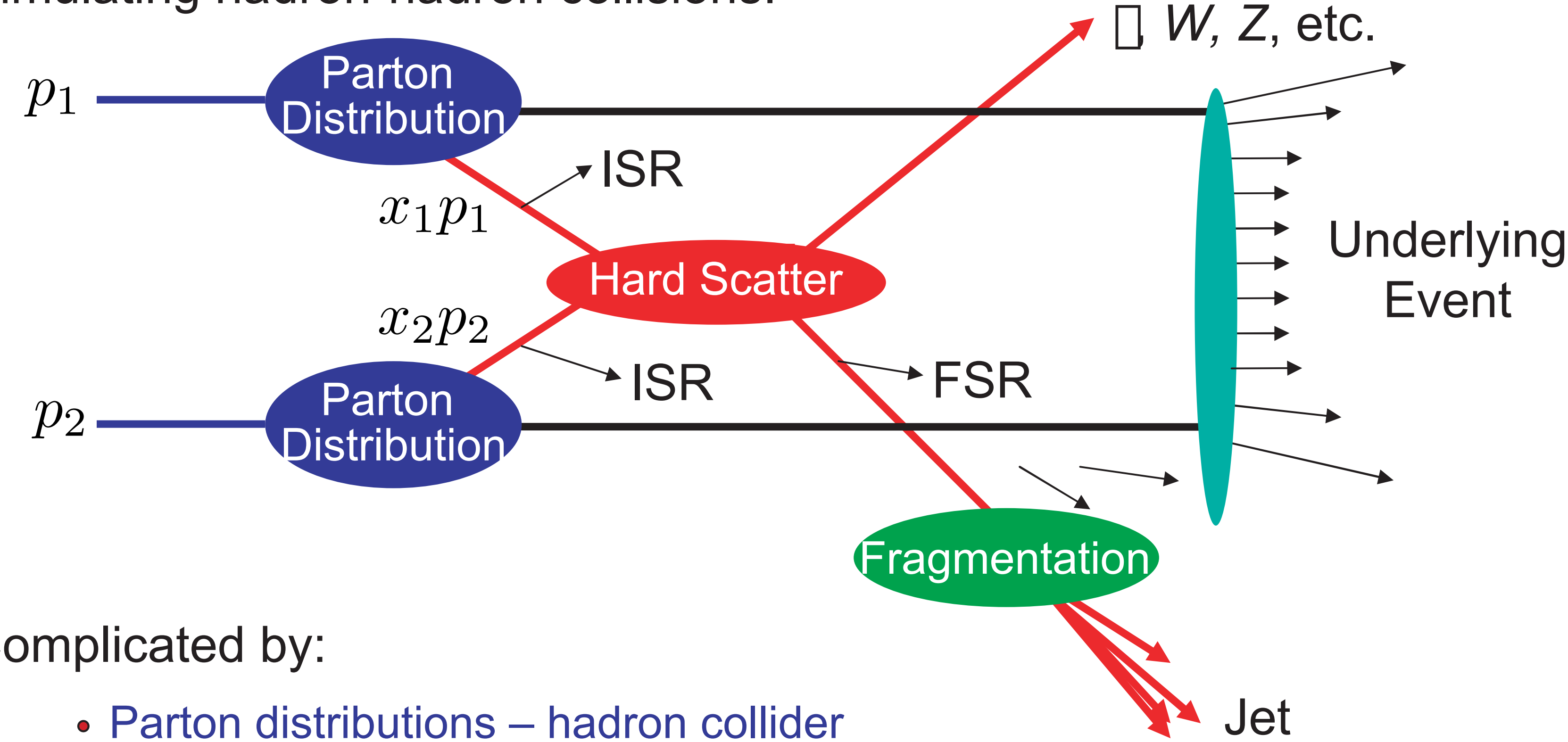
Monte Carlo Simulation

Simulating hadron-hadron collisions:



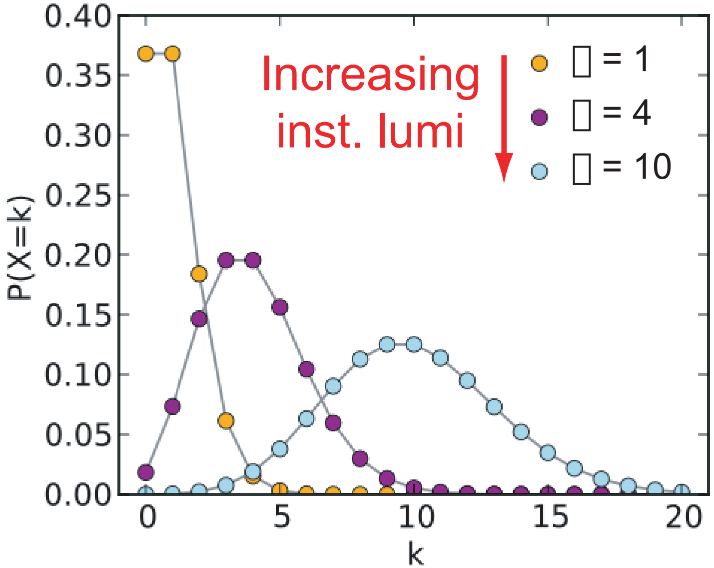
Complicated by:

- Parton distributions – hadron collider is really a "broad-band" quark & gluon collider
- Both initial and final state radiation (ISR & FSR) can have color, i.e., radiate gluons (soft jets)
- Underlying event due to proton (anti-proton) remnants

Monte Carlo Simulation

e.g., overlay/merge real pile-up events on to MC signal or background events

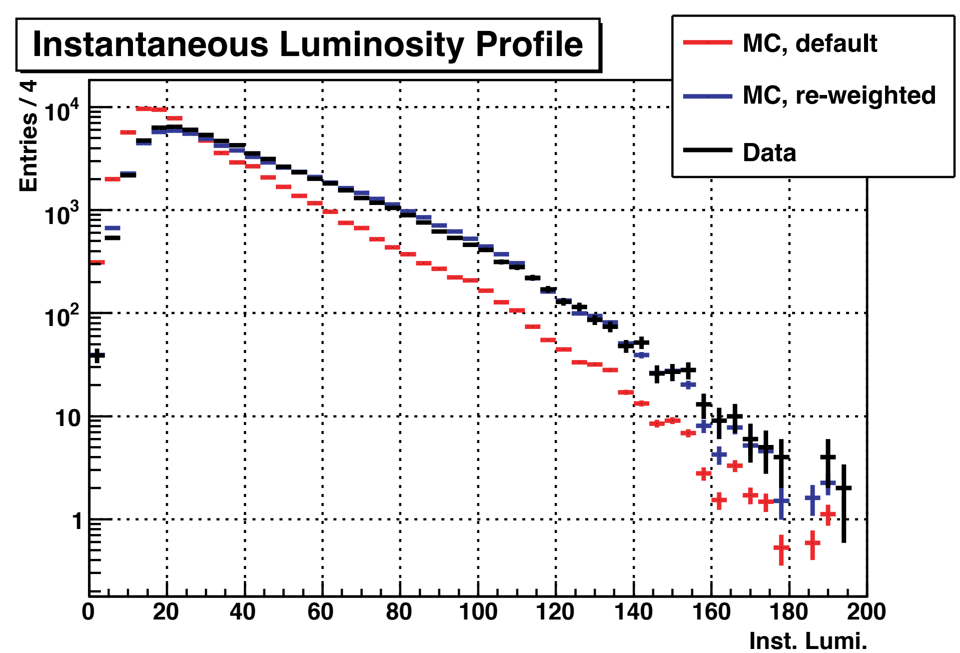
(important for isolation effic., calorimeter activity, tracking performance, triggering, etc.)



- Number of independent pile-up events, *k*, to "overlay" drawn from Poisson dist., of minimum bias triggers with λ depending on instantaneous luminosity

- If data and MC don't match? Can reweight (within reason)

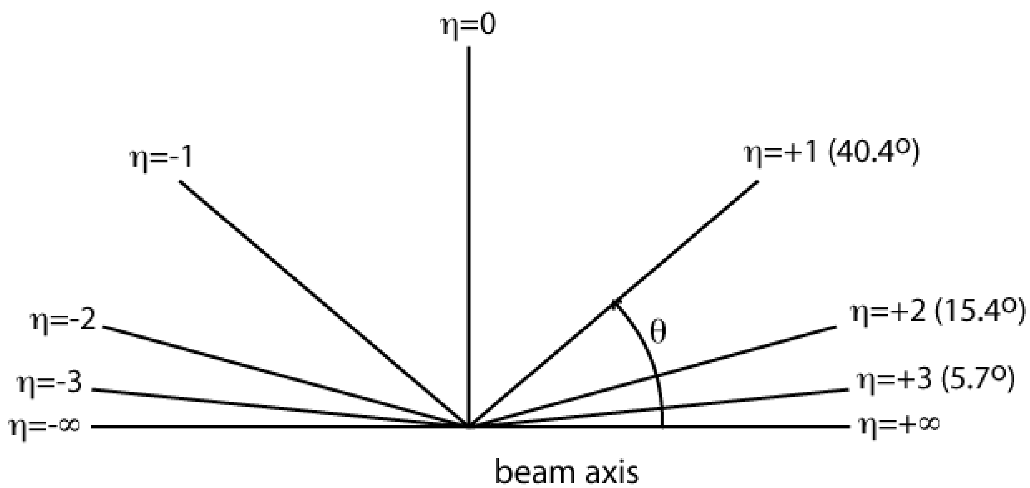
- e.g., to get to match, reweight events with smaller *k* with a weight, *W* < 1, and those with larger *k*, *W* > 1 (e.g., as entered into histogram and entire analysis)

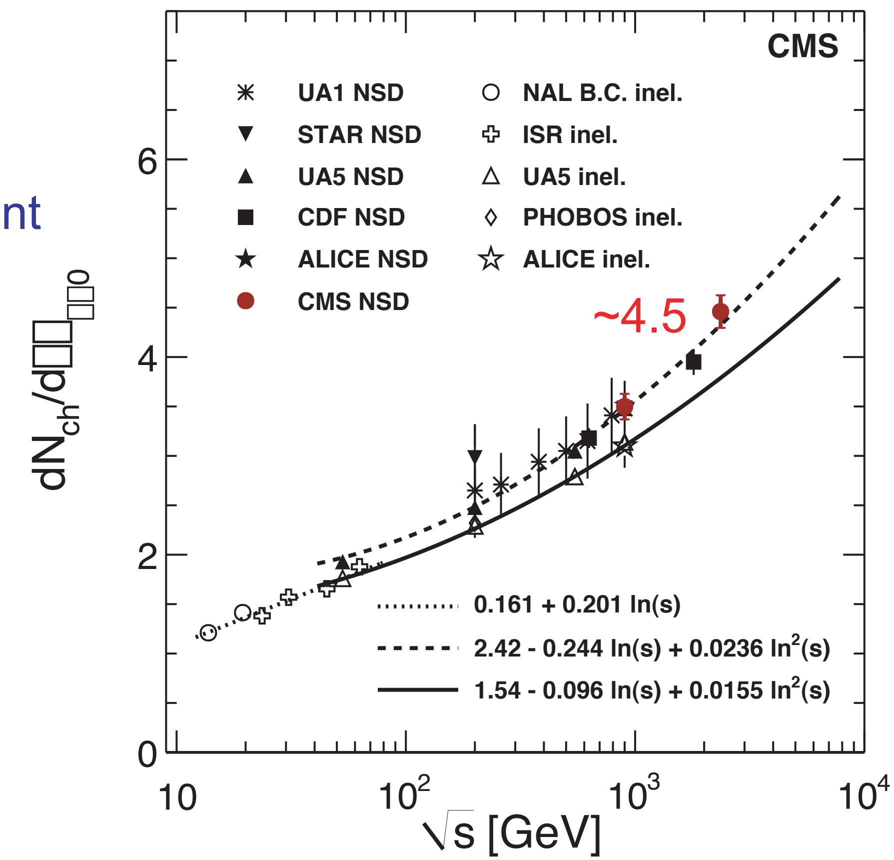


Monte Carlo Simulation

Underlying Event

- Color strings breaking lead to a sort of cloud of soft hadrons in the events
- Often think in terms of the underlying event actually being a min-bias event accompanying the hard collision (or vice versa) – not quite: color reconnection and "beam drag"
- Rule of thumb: number of particles per unit of pseudorapidity is roughly constant...but at what?





~4.5 at $\langle p_T \rangle$ ~0.5 GeV

Monte Carlo Simulation

Underlying Event

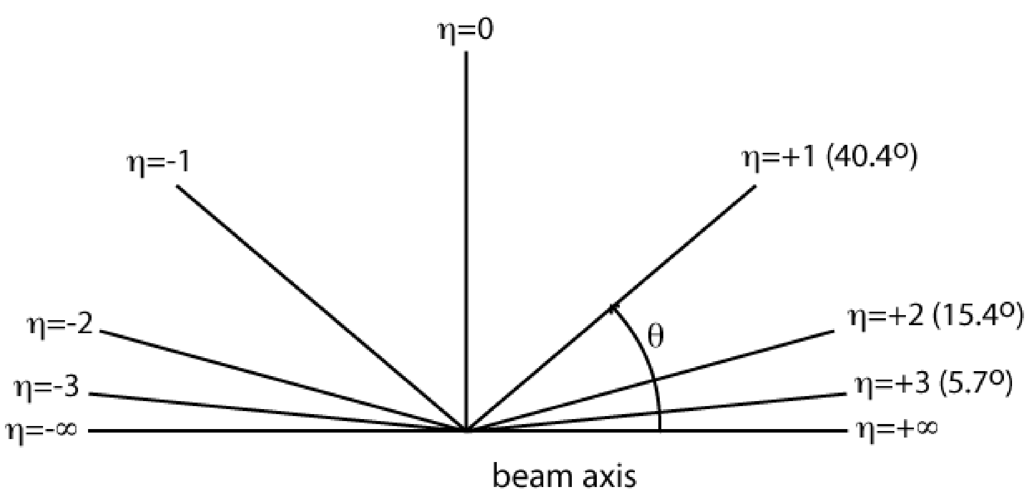
Pseudorapidity

$$\eta = \frac{1}{2} \ln \left[\tan \theta / 2 \right]$$

$$\eta = \frac{1}{2} \ln \left[\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right]$$

Rapidity

$$y = \frac{1}{2} \ln \left[\frac{E + p_z}{E - p_z} \right]$$



If $E \simeq |\vec{p}|$, then $\eta \simeq y$

Differences in rapidity are exactly Lorentz invariant

Therefore....

Monte Carlo Simulation

Underlying Event

Pseudorapidity

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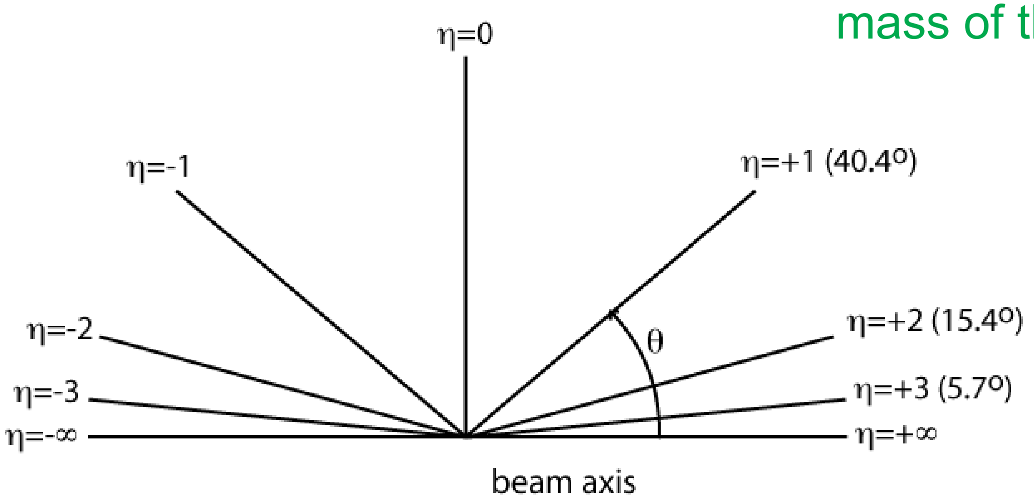


If $E \simeq |\vec{p}|$, then $\eta \simeq y$

Differences in rapidity are exactly Lorentz invariant

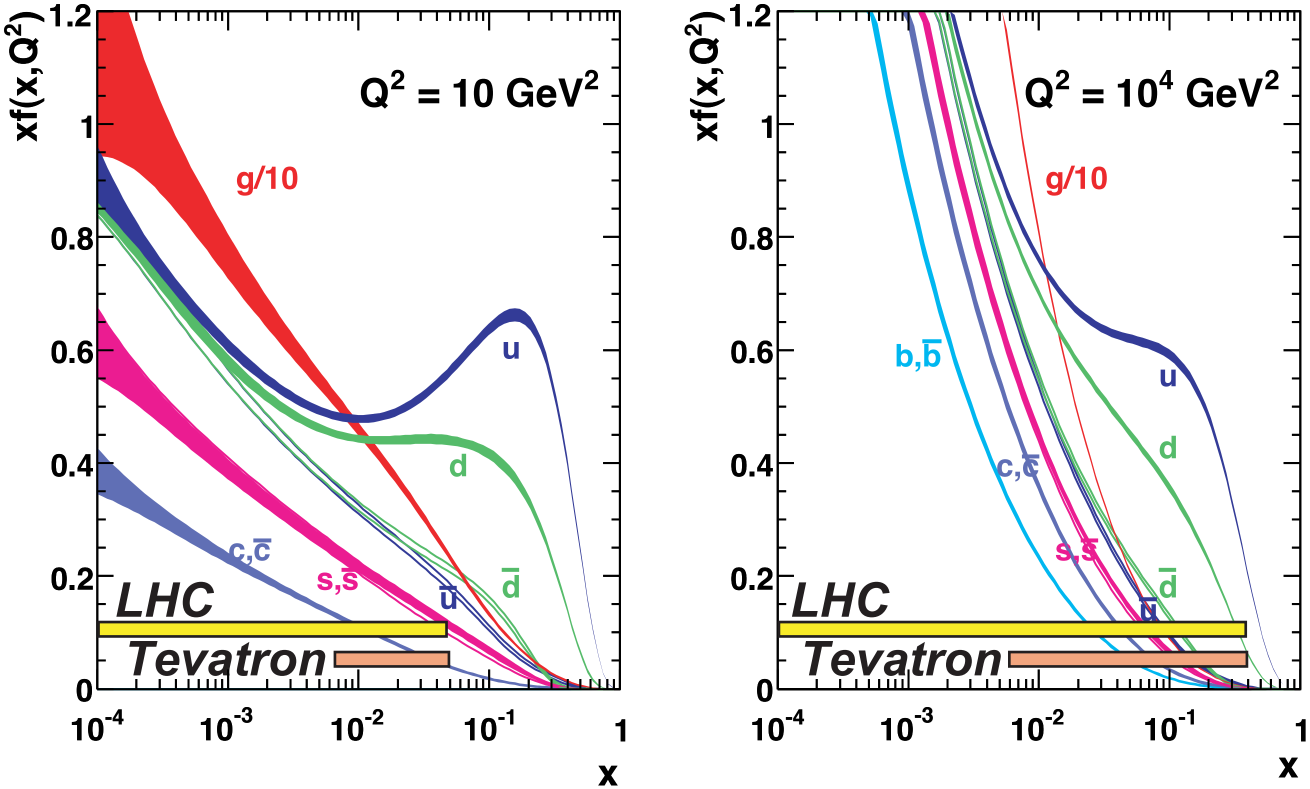
Therefore....

Starting with an isotropic distribution of particles in the rest frame of the primary, hard collision, *any* random, symmetric distributions of boosts along *z* will give the "constant particle per unit " as long as boost is large compared to the mass of the particles.

Monte Carlo Simulation

Both acceptance/efficiency *and* cross sections sensitive to PDF's

One example set and uncertainties: **MSTW 2008 NLO PDFs (68% C.L.)**



$M \approx \sqrt{Q^2}$

LHC essentially a gluon-gluon collider

- Can lead to some sizeable systematic uncertainties!!
- Other sets: CT10 (CTEQ6.6), NNPDF2.0, HERAPDF, ADKM09, GJR08
- Can access most under common interface: LHAPDF (Les Houches Accord)

Measuring a Cross Section

...or any other "absolute" measurement...

Number of observed candidates
(fitted or counted)

Number of background candidates
(measured from data
or calculated from theory)
(minimize)

Cross section in cm^2
(or □b, nb, pb)

$$\sigma = \frac{N_{\mathrm{obs}} - N_{\mathrm{backg}}}{\epsilon \cdot \int \mathcal{L} dt}$$

Efficiency/acceptance
(maximize)

Integrated Luminosity in cm^{-1}
(or □b^{-1}, nb^{-1}, pb^{-1})
(maximize,
unless systematically limited)

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{\mathrm{obs}}^2 + \delta N_{\mathrm{backg}}^2}{(N_{\mathrm{obs}} - N_{\mathrm{backg}})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

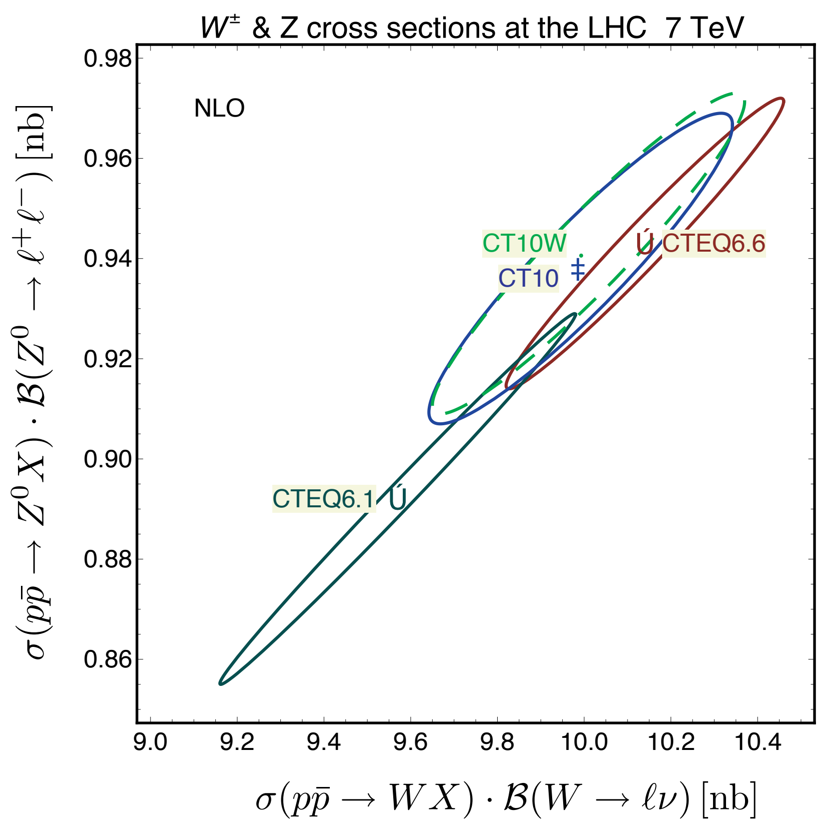
Measuring a Cross Section

Would have all the pieces together, e.g.,

$$\sigma(p\bar{p} \to Z^0 X) \cdot \mathcal{B}(Z^0 \to \mu^+\mu^-) = 265.8 \pm 1.9\,(\mathrm{stat})^{+4.5}_{-5.1}\,(\mathrm{syst}) \pm 16.3\,(\mathrm{lumi})\,\mathrm{pb}$$

Quickly dominated by systematic and luminosity uncertainty;
experimentally, ratios are preferred as luminosity uncertainty could cancel.

Although:

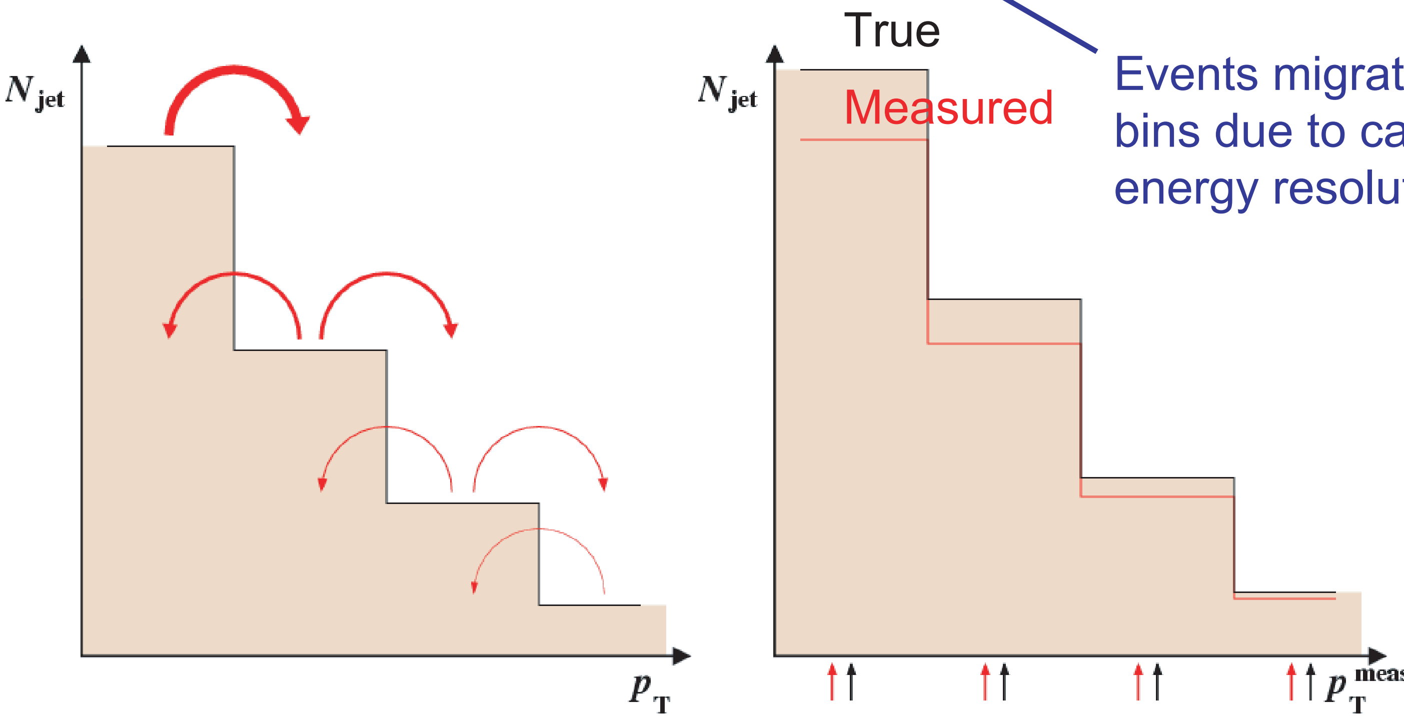


Differential Cross Section

Worry about the shape (particularly steeply falling distribution) and finite resolution:

$$\frac{d^2\sigma}{dp_T dy} = \frac{N}{\epsilon \cdot L \cdot \Delta p_T \Delta y} \cdot C_{\text{smear}} \text{ vs. } p_T$$

Events migrate between bins due to calorimeter energy resolution



We can measure the resolution in data using dijet asymmetry *A*

$$A = \frac{p_{T,1}^{jet} - p_{T,2}^{jet}}{p_{T,1}^{jet} + p_{T,2}^{jet}} \rightarrow \frac{\sigma_{p_T}}{p_T^{jet}} = \sqrt{2}\sigma_A$$

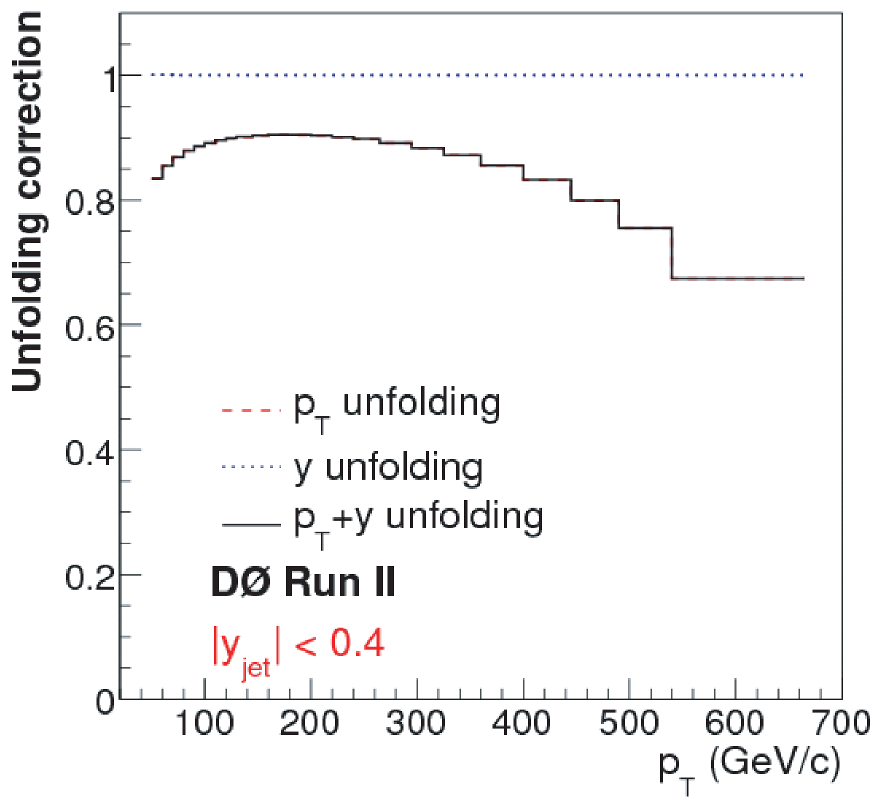
plus lots of corrections

Differential Cross Section

Unfolding

Unfold, using iterative procedure:

- Reasonable MC model (ansatz), smear with resolution
- Fit measurement
- Reweight MC to reflect data measurement; repeat



Works because large statistics, smooth; fluctuations wreck this!

Unfolding

When?

Use unfolding to recover theoretical distribution where

- There is no a-priori parameterisation (otherwise can just fit to function!)
- This is needed for the result and not just comparison with MC
- There is significant bin-to-bin migration of event

Where?

- Traditionally used to extract structure functions
- Dalitz plots: cross-feed between bins due to misreconstruction
- “True” decay momentum distributions

  Theory at parton level, we measure hadrons

  Correct for hadronisation as well as detector effects

How?

- Can sometimes get away with simple iterative procedure
- If low statistics in bins, "spiky", need to smooth $\longrightarrow$ "regularization"
- Packages out there, e.g., RooUnfold, works in root.

Outline

"Experimental Techniques" in the context of three quite very different types of analyses, seguing into topics important for that kind of analysis

"Absolute", e.g., measuring a cross section $\sigma(p\bar{p} \to Z^0 X) \cdot \mathcal{B}(Z^0 \to \mu^+\mu^-)$

- Instantaneous & integrated luminosity (see Prebys talk for getting there)
- Triggers (efficiency & combining) (for rest see Vachon's talk)
- Efficiency / acceptance
- Monte Carlo simulations
- Unfolding

Measuring particle properties: e.g., B_s^0 lifetime, Top quark mass, W mass

- Scales
- High p_T b-jet tagging, jet def'ns
- Different ways to extract from observables
- Blind analyses
- Systematic Uncertainties

Experimental Scales

Measuring cross sections & related, critical:

- integrated luminosity
- triggers and overall efficiencies/acceptances

Experimental Scales

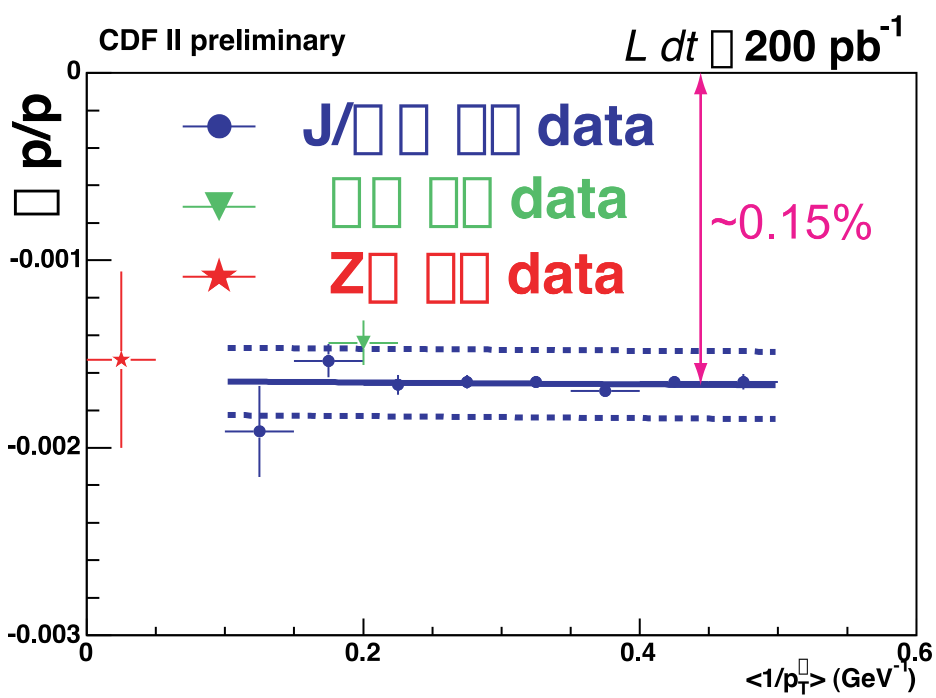
Lots of LHC detector activity!

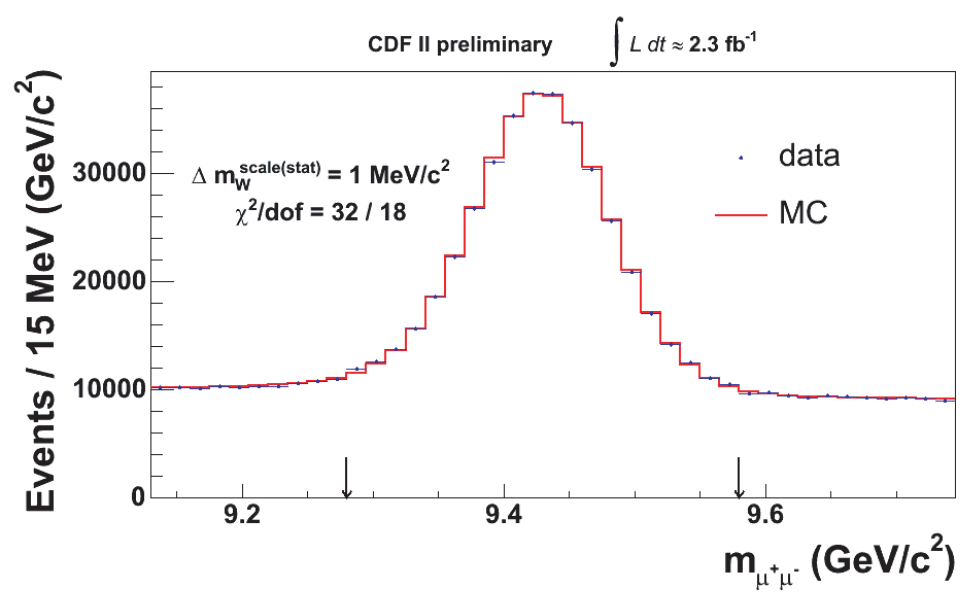
Measuring particle properties? Different set of "absolutes" needed/important and for all relevant (□,□,*r*)

- Charged track momentum scale: uncertainties in $\vec{B}$ field, alignment, material

  Reconstruction of known mass peaks:

  $$Z^0, \Upsilon(4S), J/\psi \rightarrow \mu^+\mu^- \;\; K^0_S \rightarrow \pi^+\pi^-$$





Was with 200 pb^{-1}, now ~3 times better precision with 2.3 fb^{-1}

Experimental Scales

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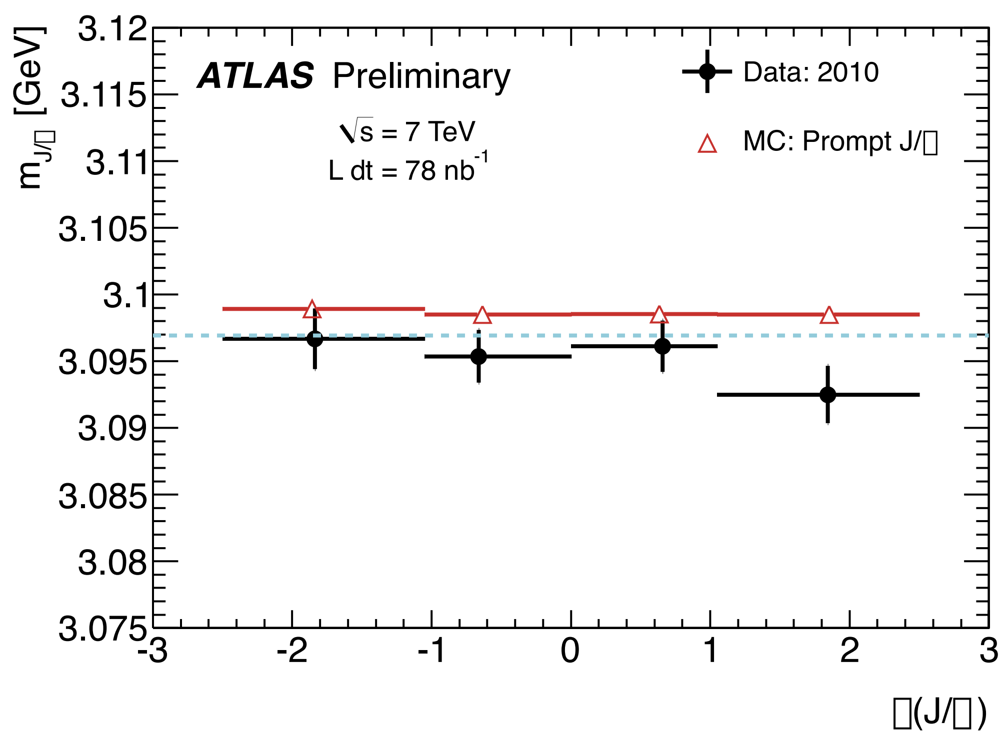


Experimental Scales

- Lifetimes: systematic shifts in alignment

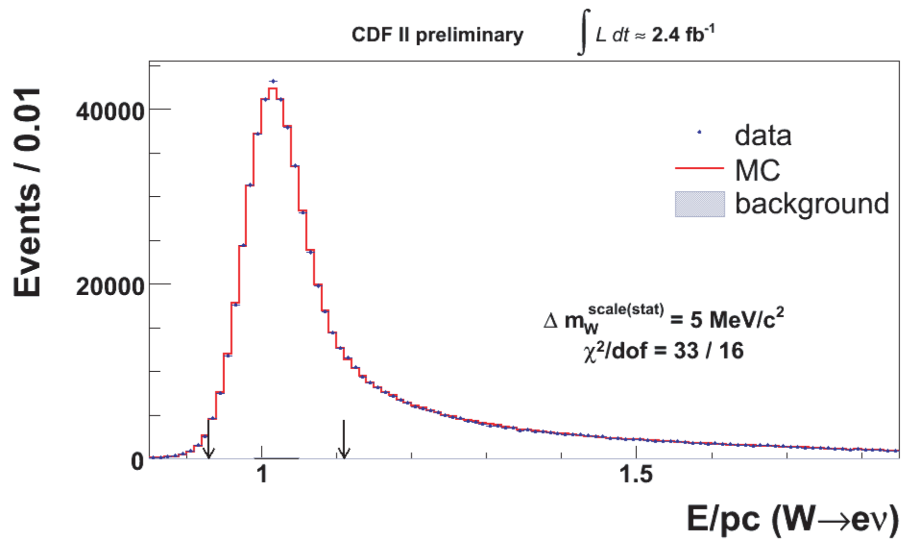
  Measurement of known lifetimes

- Electron energy scale: uncertainties in material, showering, response, noise

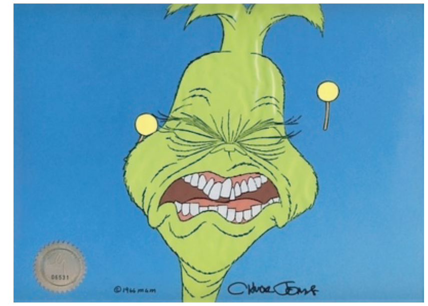
  Reconstruction of known mass peaks:

  $$Z^0, \Upsilon(4S), J/\psi \to e^+e^-, \quad W \to e\nu$$

  Compare *E* to *p* for electrons (particularly high-energy where good *E* resol.)



Experimental Scales



- Missing E_T calibration (zero when it should be zero!)

  Noise, noise, noise; calorimeter efficiencies/inefficiencies

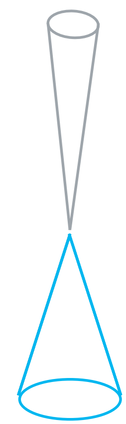
- Jet energy scale (□,□)

largest component in transformation is overall scale R

$$E_{\rm jet}^{\rm meas} \longrightarrow E_{\rm jet}^{\rm ptcl}$$

$$p_{T,{\rm jet}}^{\rm meas} \longrightarrow p_{T,{\rm jet}}^{\rm corrl}$$

e.g.: "in situ" in analysis (later); and/or independently:



Measuring a Lifetime

Fitting to a functional form (+ typical analysis steps)

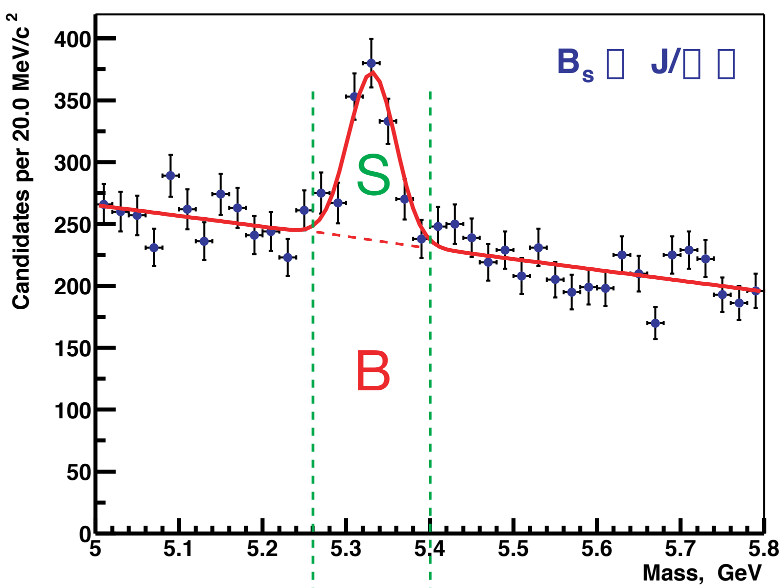
Lifetime of B_s^0 hadron in decay mode $B_s^0 \to J/\psi\,\phi$

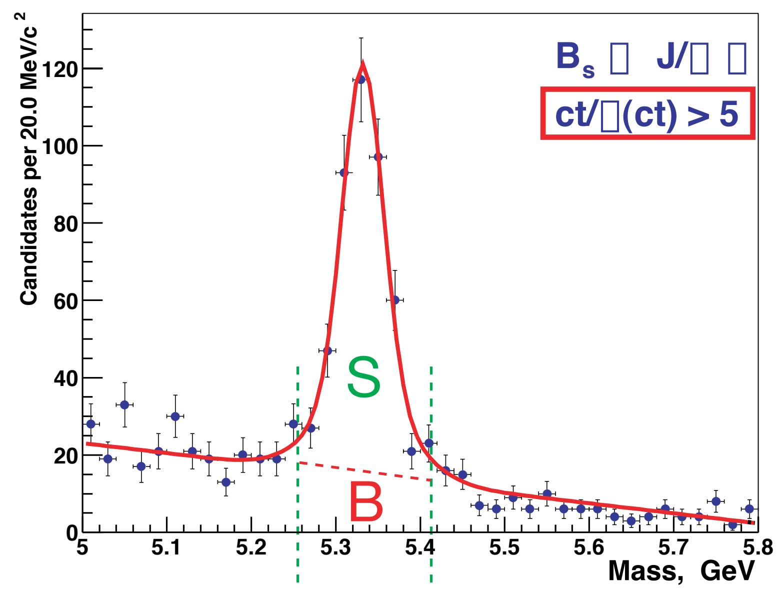
Measuring a Lifetime

There will always be backgrounds!

- True physics backgrounds that looks just like your signal (irreducible)
  (but look for an excess of events above these other physics processes)
- Random combinatorics of tracks and energy clusters that just happens to "fake" the topology of your signal

Find a selection that greatly reduces no . of background events without too much decrease in number of signal events, e.g.:

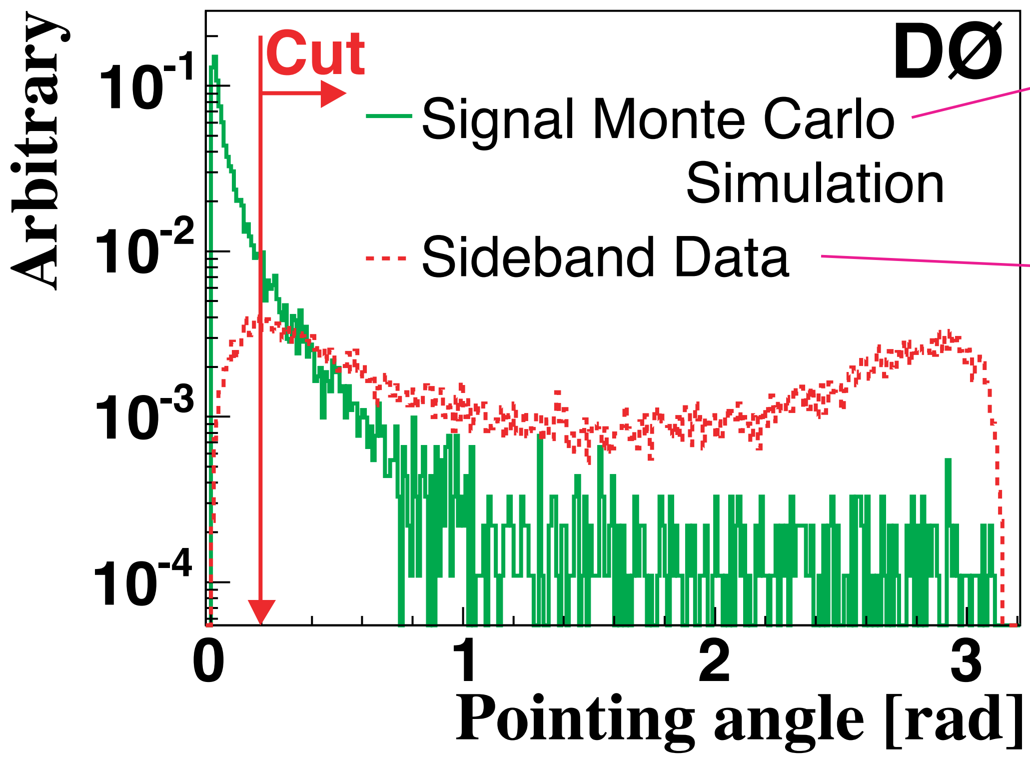




Measuring a Lifetime

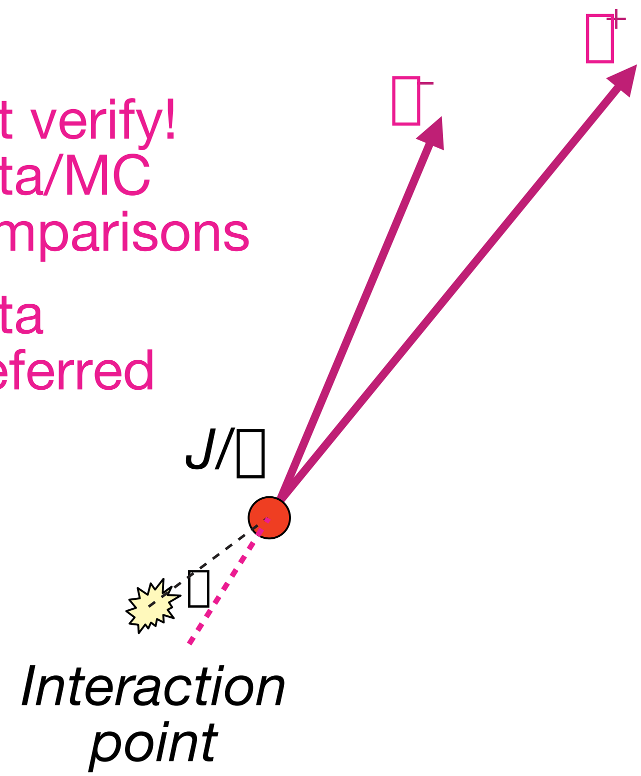
How to find the event variables to select on to reduce background?
e.g.:

Simplest "square cut": how to optimize? More later



But verify! Data/MC comparisons

Data preferred

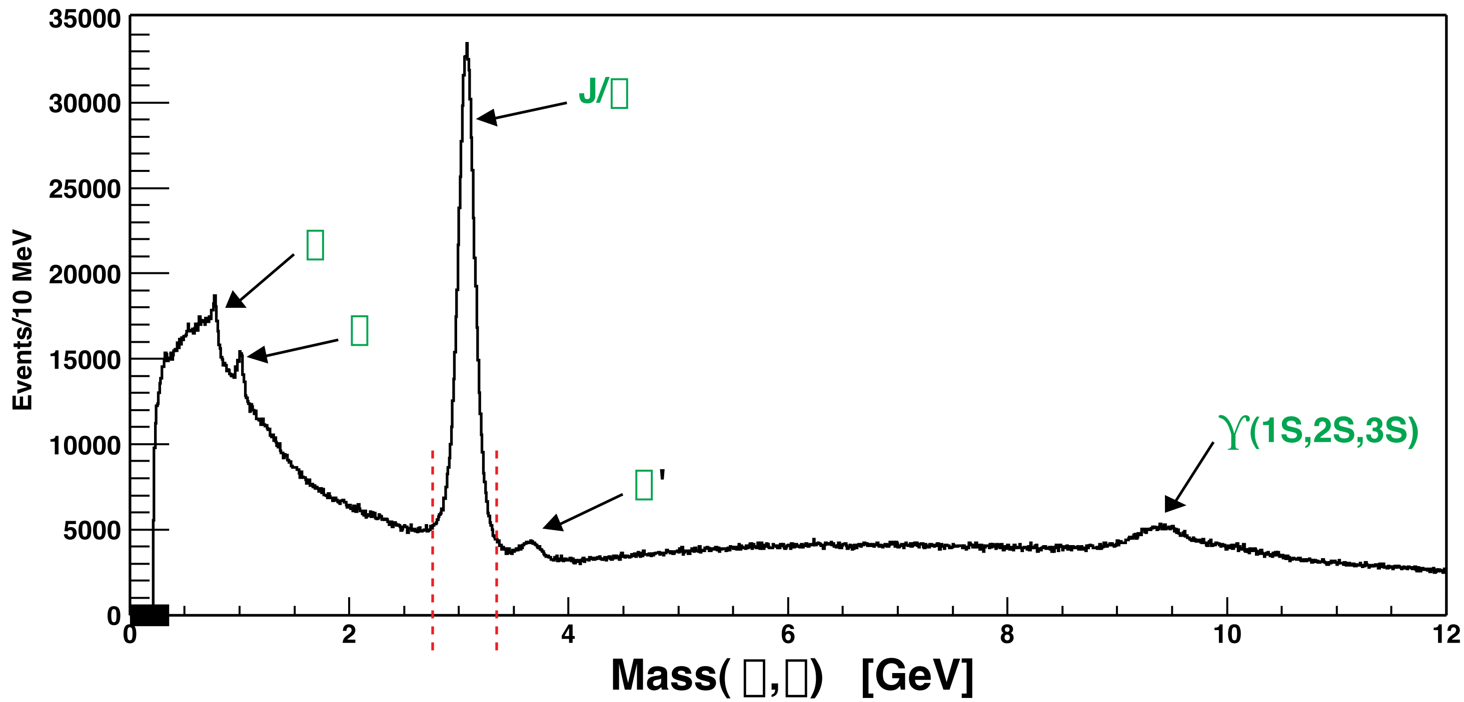


Note that the absolute efficiency of the cut is not so important as is signal/background separation

Measuring a Lifetime

Reconstruct the decay products:
$J/\psi \to \mu^+\mu^-$

- Start with dimuon sample (any dimuon trigger, but will take *any* trigger giving an offline dimuon as long as it does not bias lifetime, e.g., if fires *only* on an impact parameter trigger)



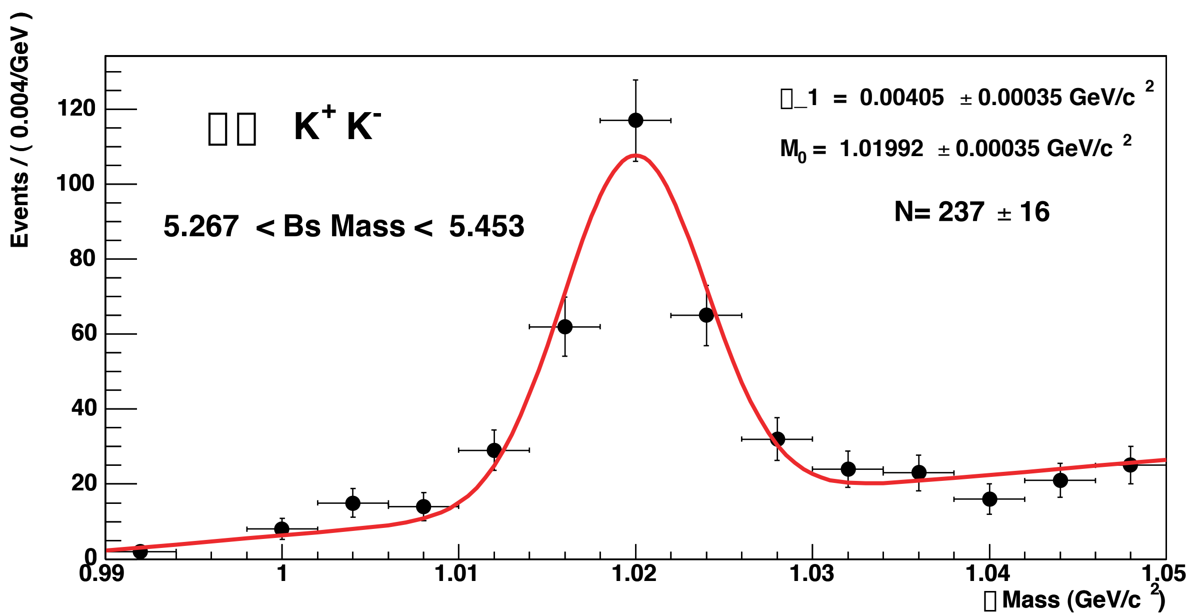
- oppositely-charged, identified muons
- $p_T(\mu) > 2.0$ GeV
- good vertex fit

Measuring a Lifetime

Reconstruct the decay products:

$\phi \to K^+K^-$

- DØ doesn't have particle identification for the kaons; therefore, loop through all the charged tracks, take the p_x, p_y, p_z measurements; assume the kaon mass to find E_K, combine with each of the all the other tracks, form the invariant mass in events that contain J/ψ candidate:

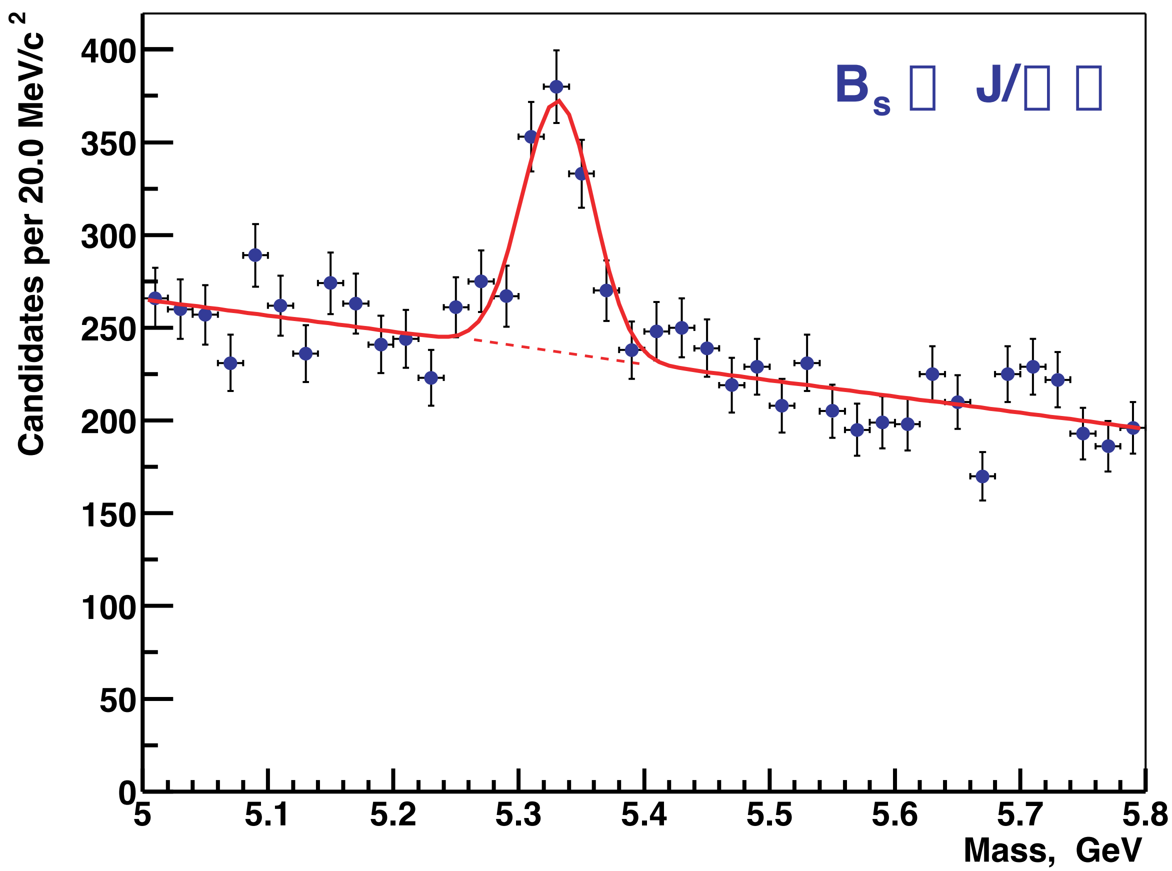


Uh, an old analysis ⟶ think early days LHC!

Measuring a Lifetime

Reconstruct the particle of interest

- Combine the 4-vector of the J/□ candidate and □ candidate. Now have the reconstructed □□= $p/m_{B_s^0}$ of the B_s^0 candidate.

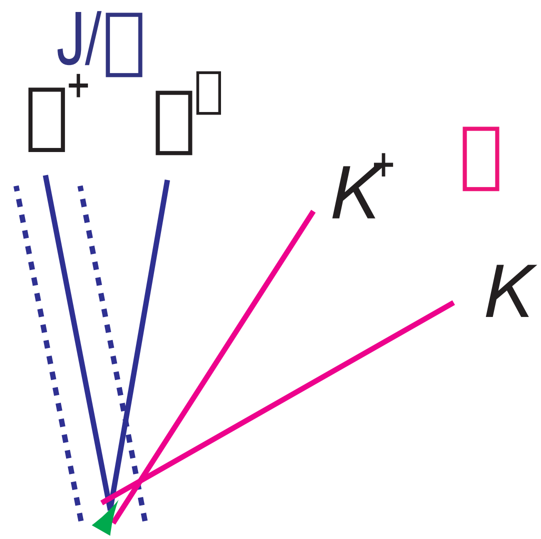


Measuring a Lifetime

Find Decay Length for each candidate

Track parameter uncertainties; see Mike Hildreth's talk

e.g., $\sigma(d_0)$

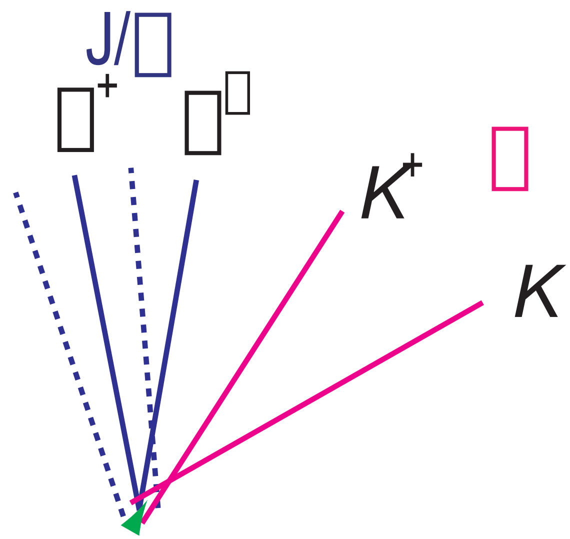


Measuring a Lifetime

Find Decay Length for each candidate

Curvature
uncertainty, □(□)

e.g., □($□_0$)



Measuring a Lifetime

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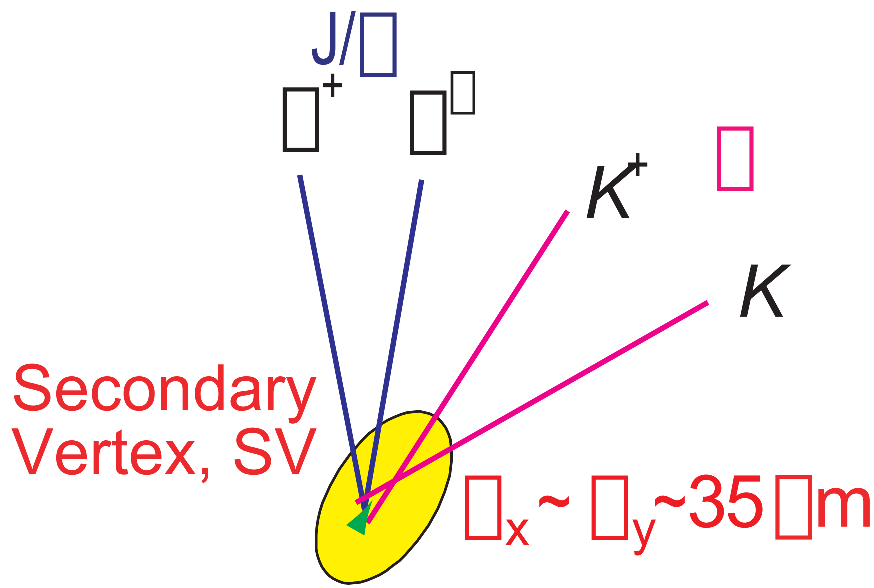

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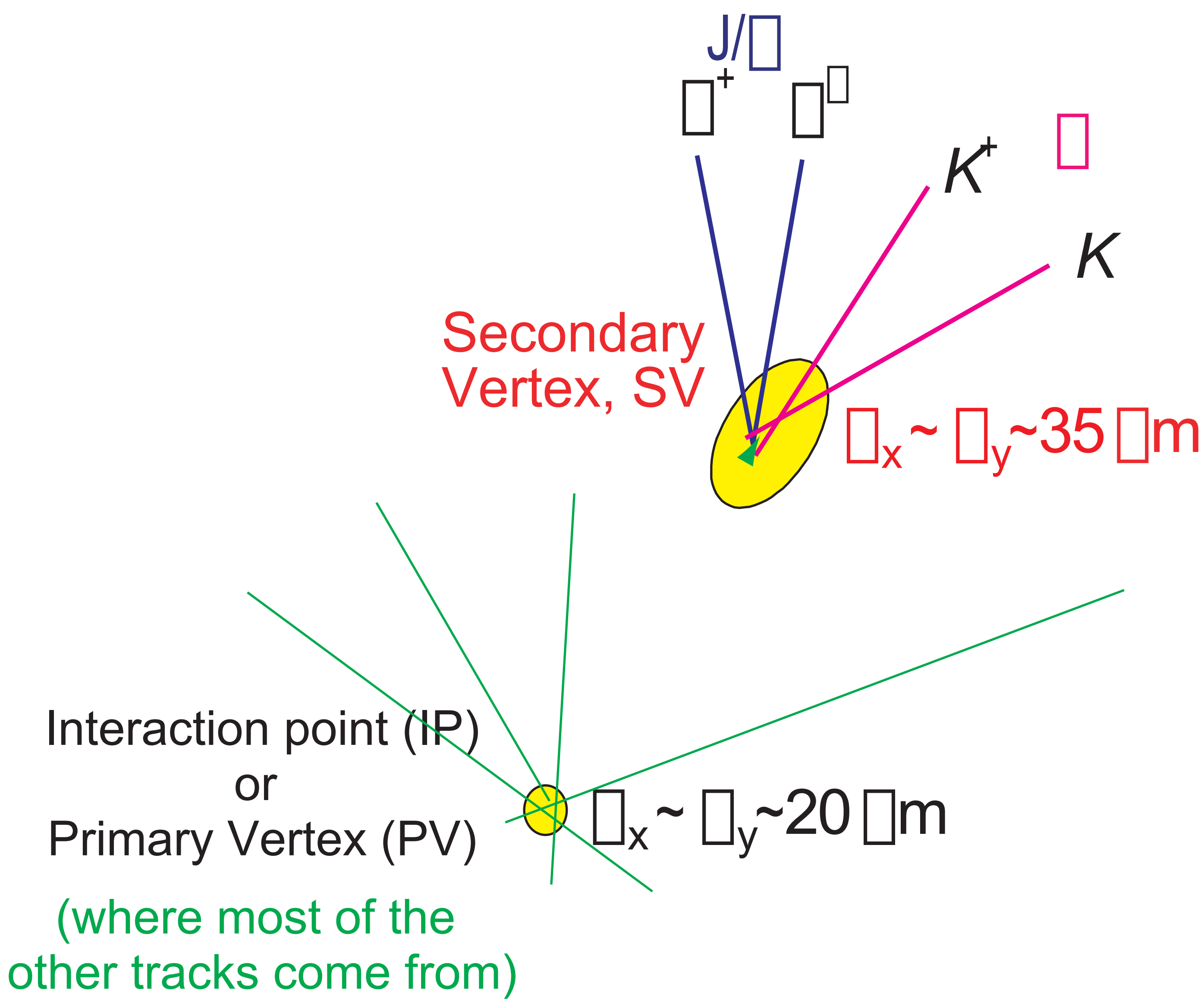
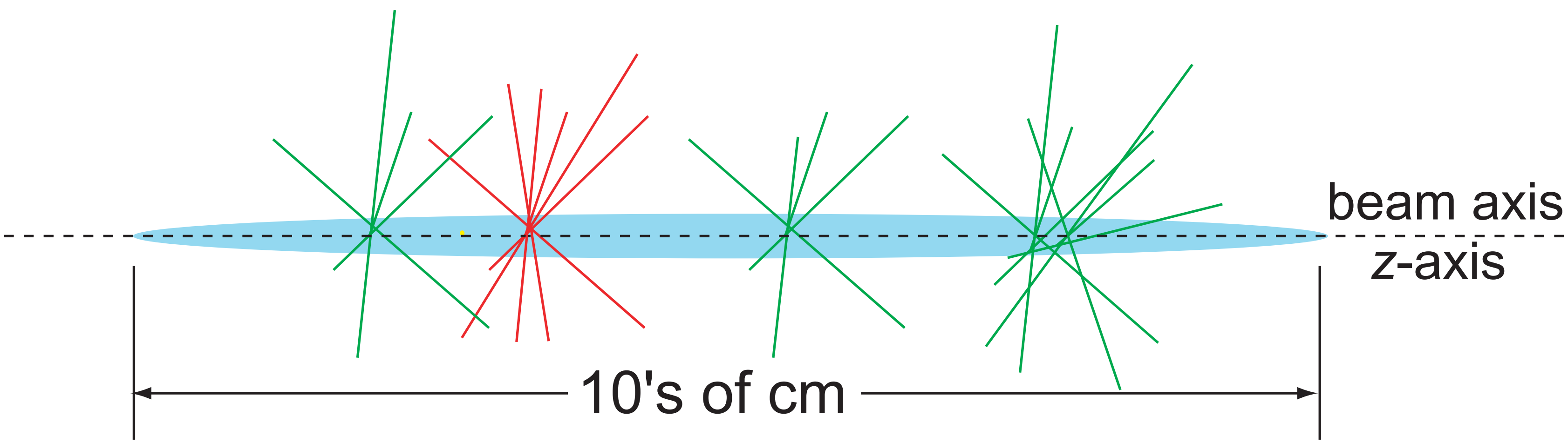


Measuring a Lifetime

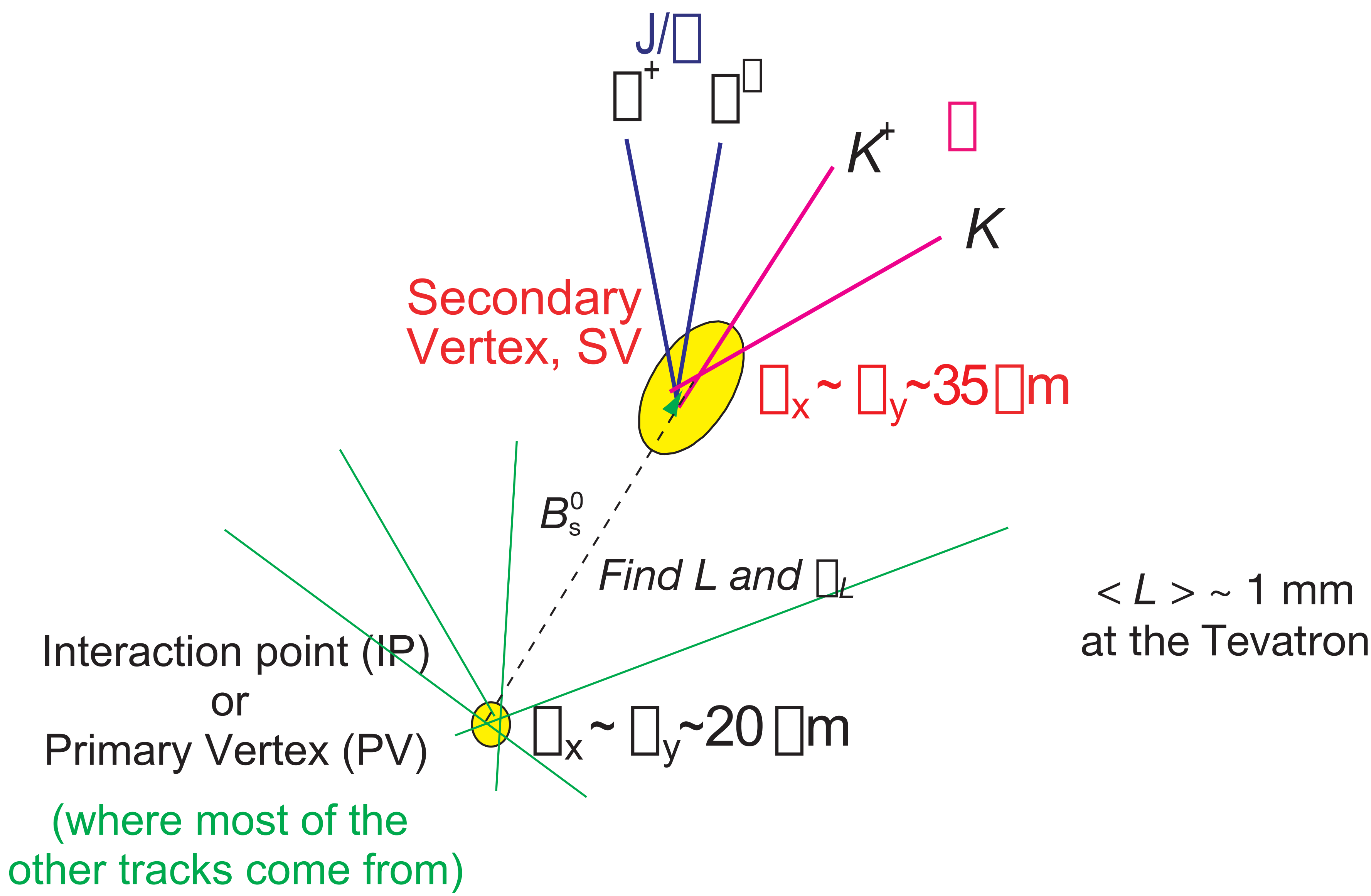
What about pileup?
(True for all higher-lumi hadronic collision events)

Precision on different PV's in *z* usually adequate to separate them
(and "interesting" collision usually has higher multiplicity, higher p_T tracks)



Measuring a Lifetime

Find Decay Length for each candidate



Measuring a Lifetime

Find Proper Decay Time for each candidate

- Decay Length, $L_i = v_i t_i$

$$L_i = \beta_i c t_i$$

...but have to take relativistic time dilation into account

$$t_i \rightarrow \gamma_i t_i \qquad L_i = \beta_i \gamma_i c t_i$$

$$\boxed{t_i = \frac{L_i}{\beta_i \gamma_i c}} \qquad \beta_i \gamma_i = \frac{p_i(B_s^0)}{m(B_s^0)}$$

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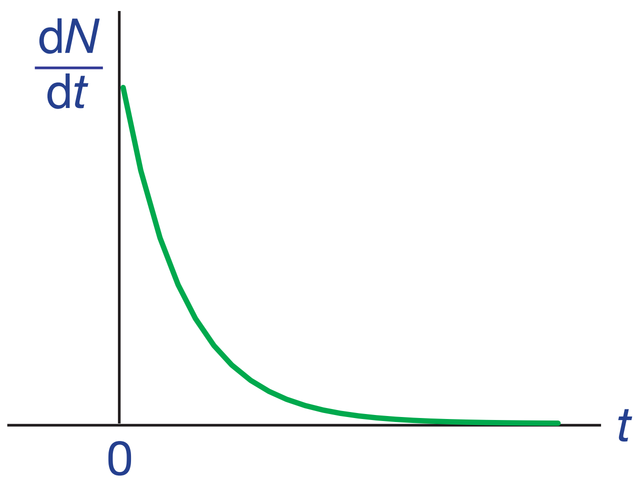
- $$\frac{dN}{dt} = \exp(-t/\tau)$$



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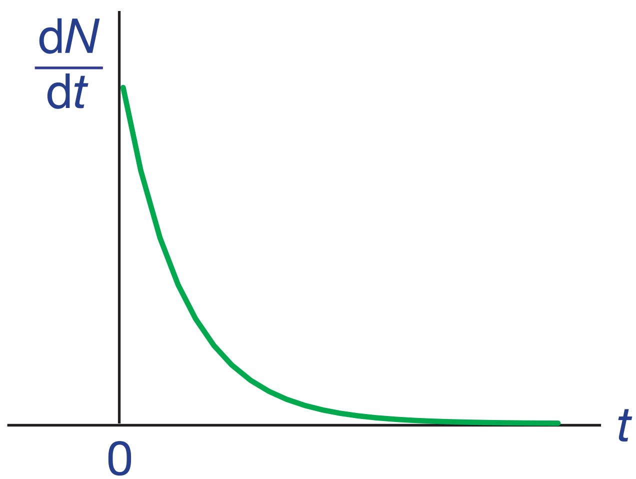
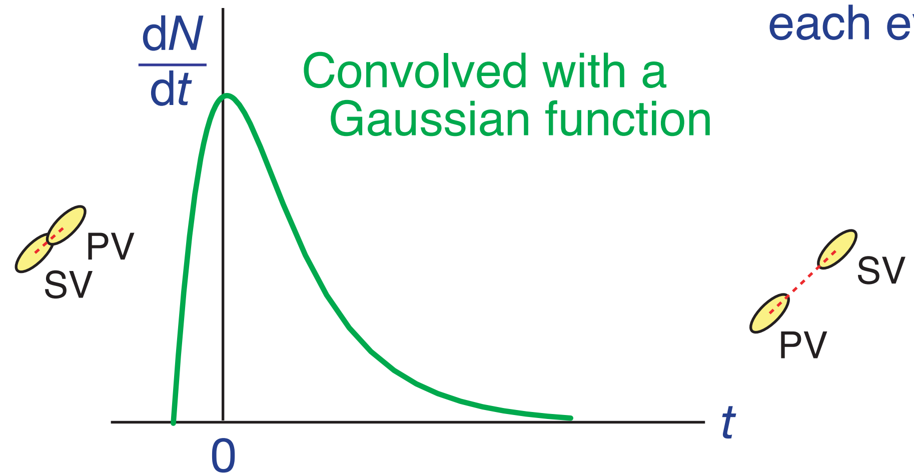


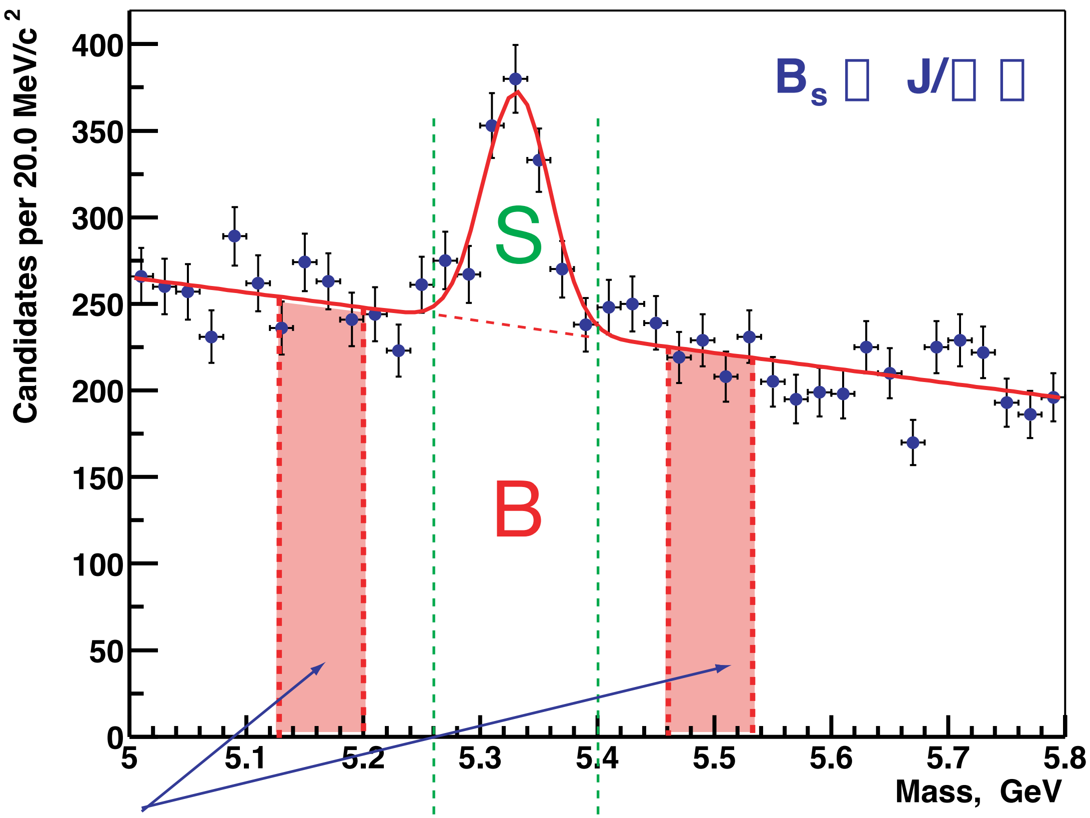
- But uncertainty, σ_L results in σ_t, resolution different each event



Functional form for fitting (of signal)

Measuring a Lifetime

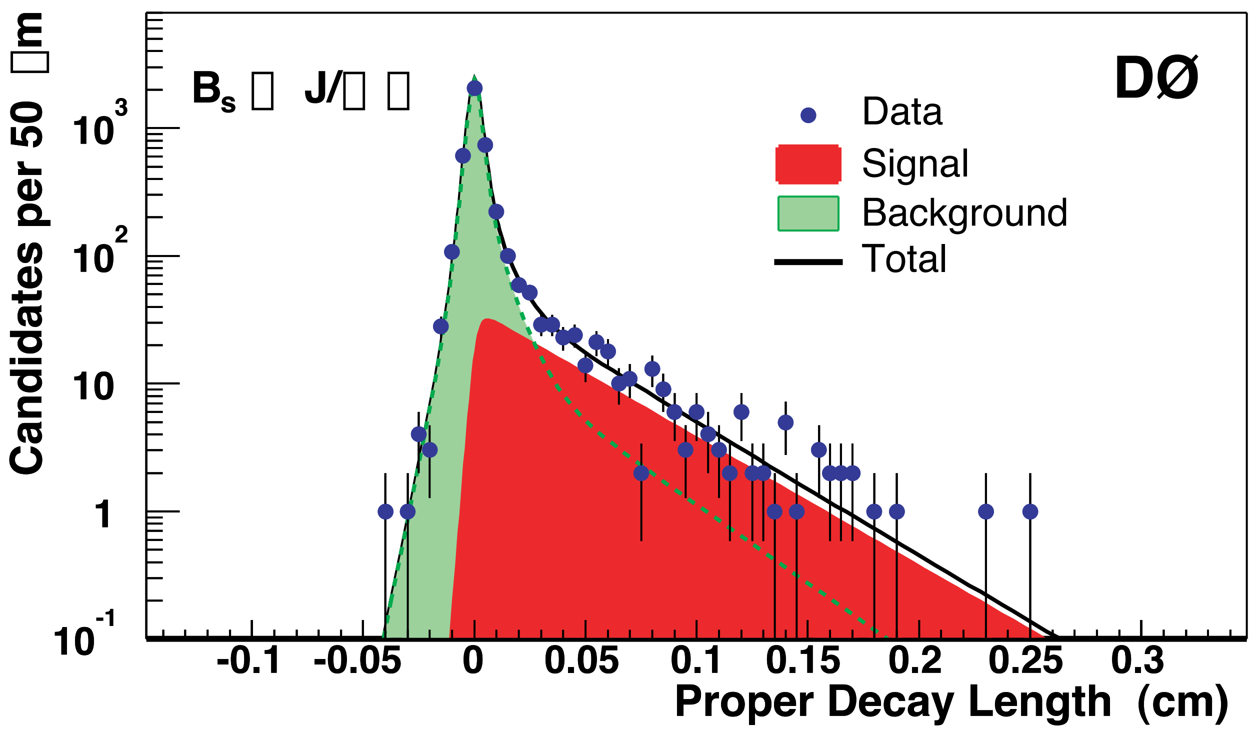
Find Level and Shape of Background "lifetime" distribution



- Use "sidebands" in invariant mass to determine background shape, vary normalizations of shape
- Better: unbinned likelihood fit simultaneously to mass and lifetime distributions, the fit knows the signal/background ratio from where an event is in the mass distribution

Measuring a Lifetime

Likelihood fit for "slope" of exponential signal

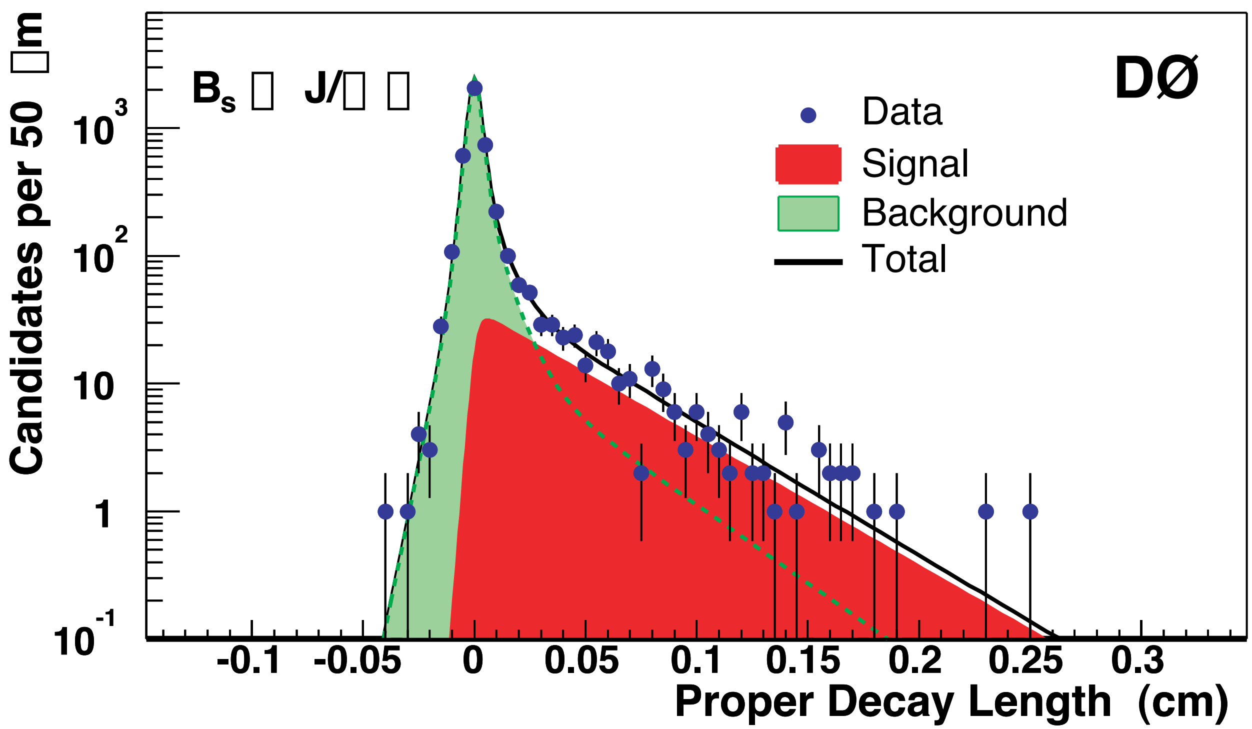


$$\tau(B_s^0) = 1.44\,^{+0.10}_{-0.09}\ \text{ps}$$

Measuring a Lifetime

Likelihood fit for "slope" of exponential signal

Fitting for a functional form

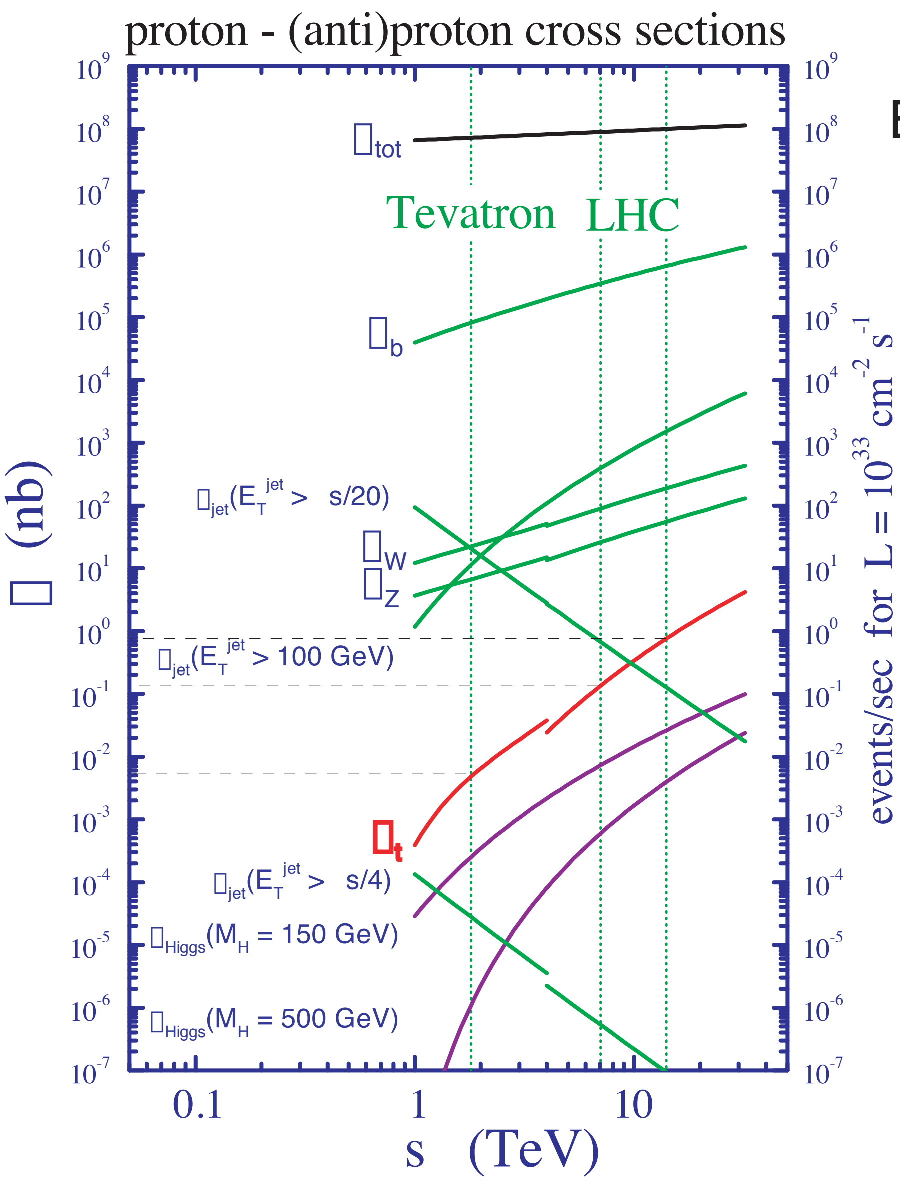


Systematic Uncertainties (can easily take > 50% of effort, and ***much*** more if not stats limited like here)

- Alignment
- Modeling uncert.
- Selection biases
- "Feeddown" or "reflections"

$$\tau(B_s^0) = 1.44\,^{+0.10}_{-0.09} \pm 0.02\ \text{(sys) ps}$$

Top Quarks



The top quark and its properties (particularly mass) are inherently interesting in the SM

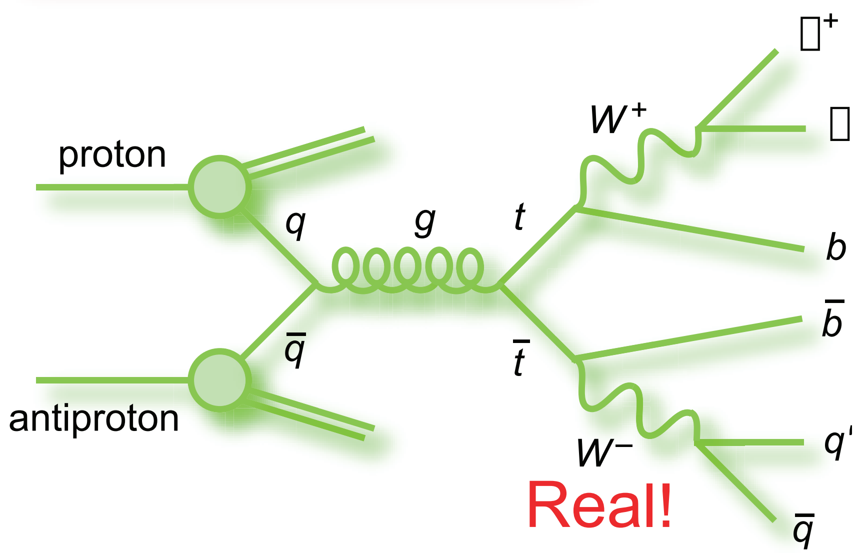
Experimentally, there will be lots more at the LHC (with, in general, less fractional backg. – see slopes)

Physics studies will continue at Tevatron and LHC; but other items of importance at the LHC:

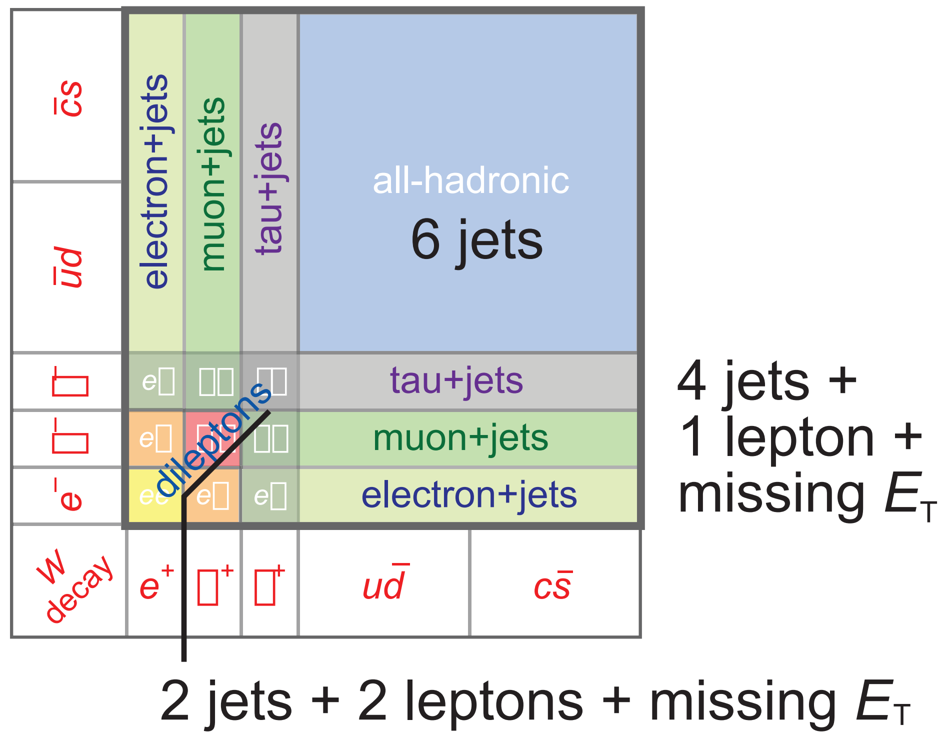
- Certify detector performance
- Calibrate light jet energy scale
- Calibrate *b*-tagging effic. & purity
- Larger background to Higgs and other new physics

- more events to measure top quark properties

Top Quarks



Top Pair Decay Channels



"Darling" of the decay channels

- Single high-p_T isolated lepton
  easy to trigger on
- Only one escaping neutrino
- Two *b* jets to reduce combinatorics
  (which jet belongs to what?) →

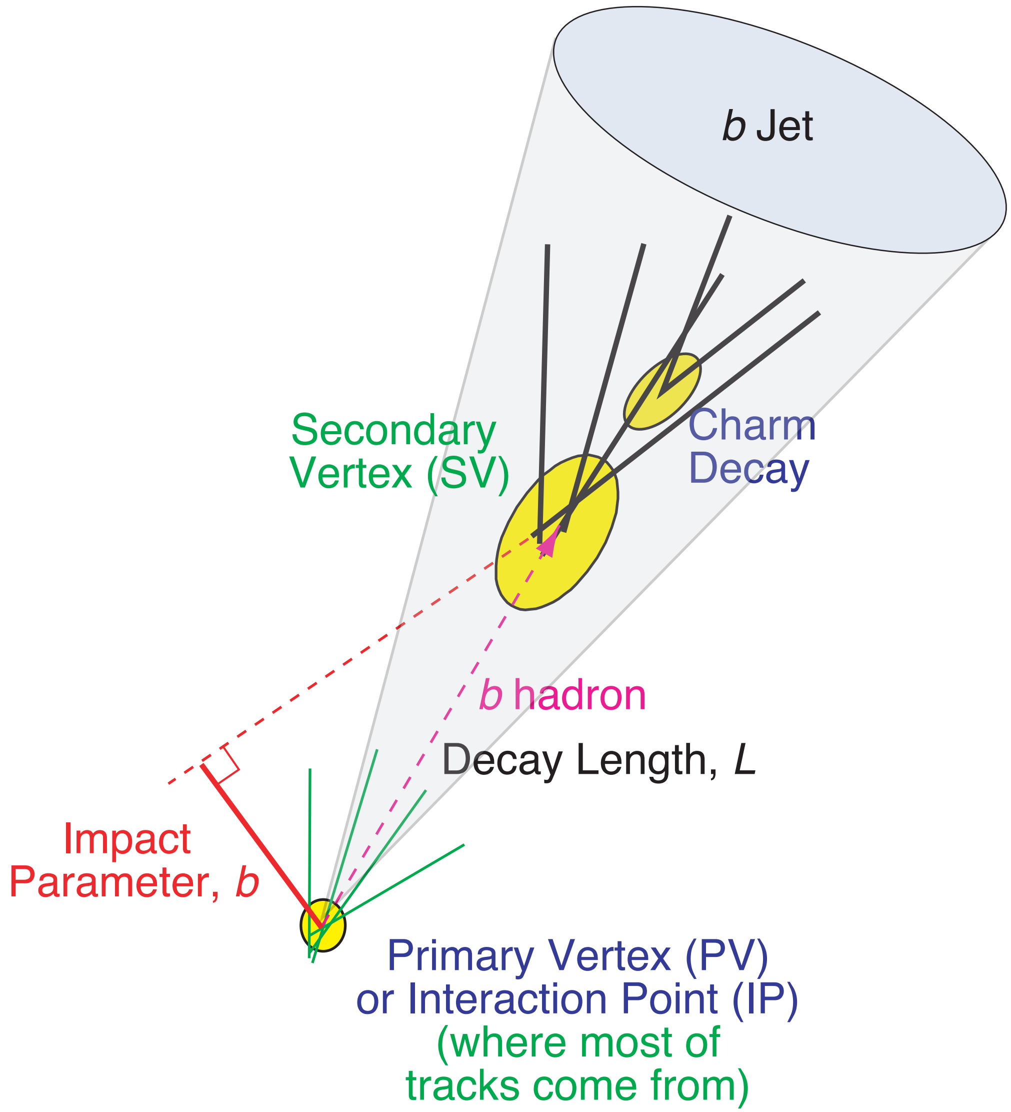
Zero *b*-tags → 12 combinations
One *b*-tag → 6 combinations
Two *b*-tags → 2 combinations

(Dilepton final state has smallest background...)

b-jet tagging →

***b*-Jet Tagging**

Also important for light SM Higgs, $t\bar{t}H_{\hookrightarrow b\bar{b}}$, SUSY, SUSY Higgs



- Hard *b* fragmentation, $\frac{p(b\,\mathrm{hadron})}{p(b\,\mathrm{quark})} \gtrsim 0.70$

  Decay products have large *p*, large sec. vertex. multiplicity

- Large *b* quark mass

  Decay products have large p_T with respect to jet axis

  Large invariant mass of sec. vertex

- *b* hadron decays semileptonically

  $$b \longrightarrow \ell,\ b \longrightarrow c \longrightarrow \ell$$

  ~10%

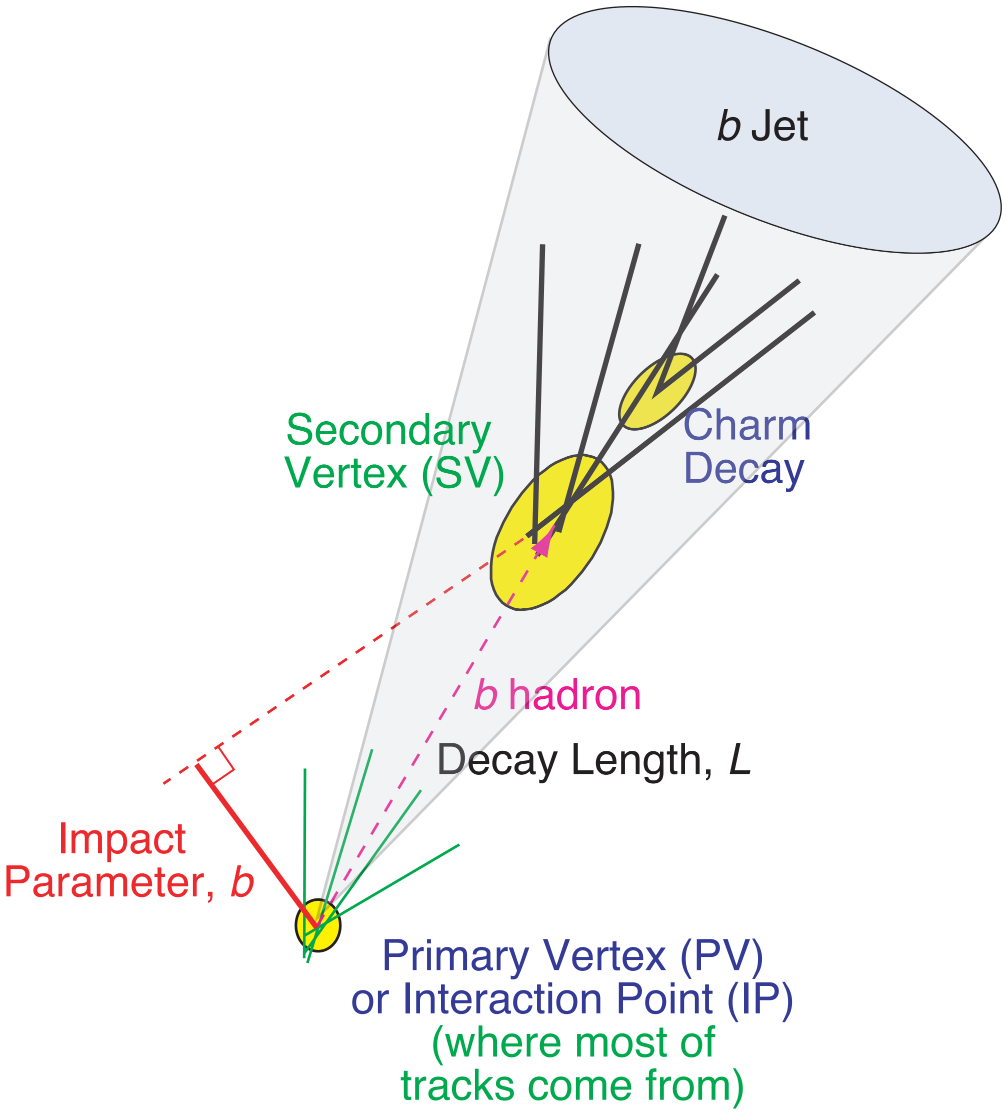
- Long *b*-hadron lifetime: $\langle L \rangle \approx 0.5 - 3.0\,\mathrm{mm}$

  Long decay lengths

  Many tracks with large impact parameters

b-Jet Tagging

Also important for light SM Higgs, $t\bar{t}H \hookrightarrow b\bar{b}$, SUSY, SUSY Higgs



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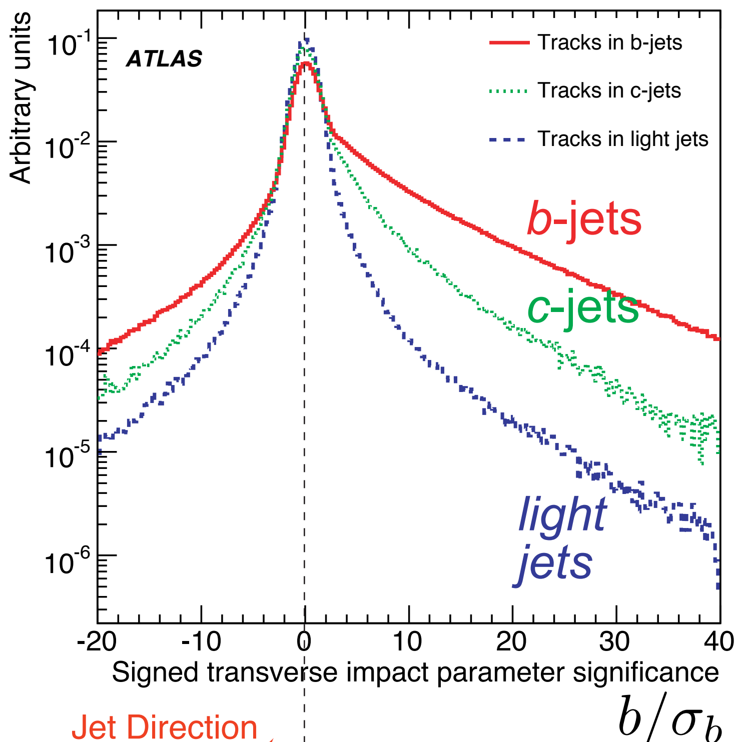
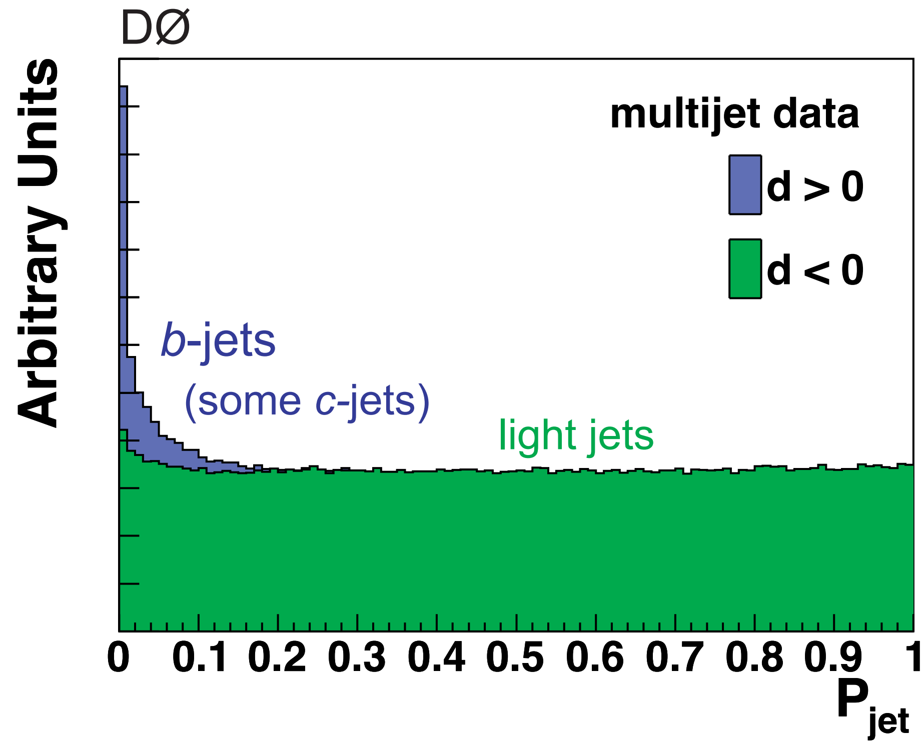
  Decay length Significance: L/σ_L

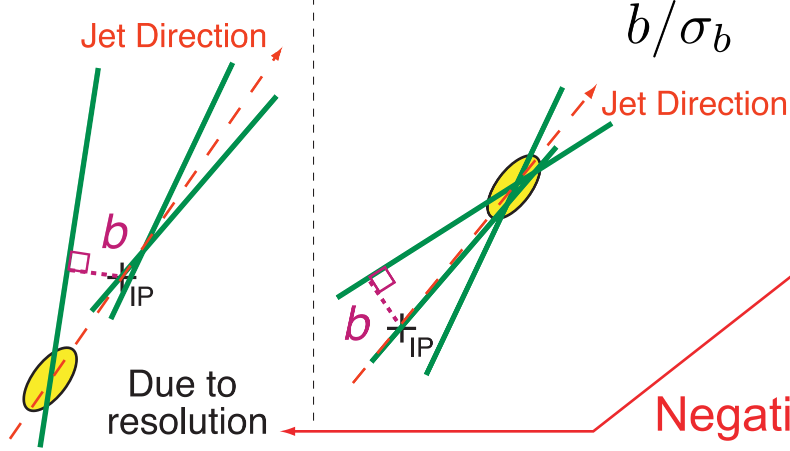
  How many tracks with large impact parameter significance: b/σ_b

  ...in 2-dim (*x*,*y*) or 3-dim

b-Jet Tagging







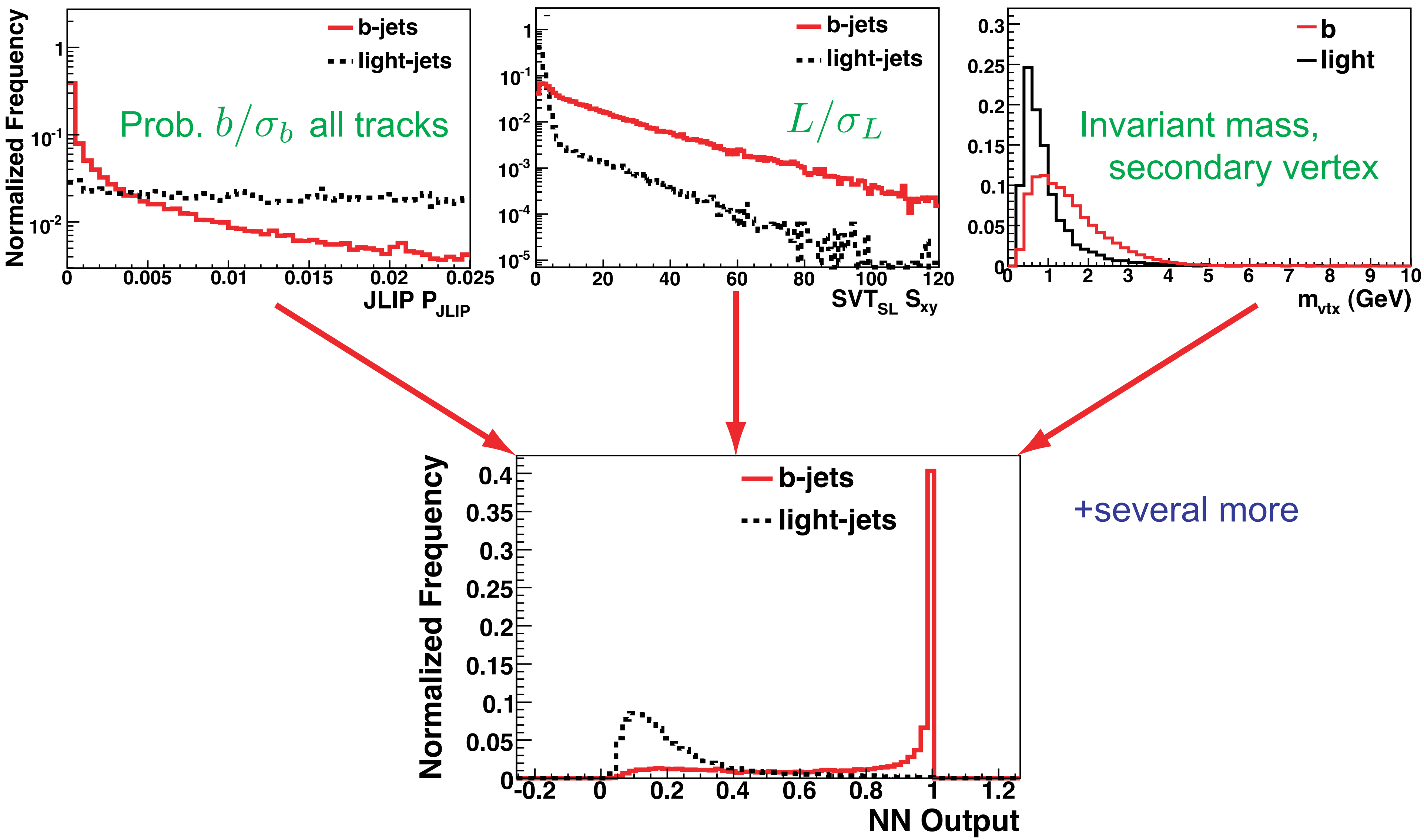
- For each track in jet, use its b/σ_b to find probability that came from IP, total probability over all tracks

Negative regions, use to find fake rate

***b*-Jet Tagging**

Inevitable: combining correlated distributions for separation

→ ***neural net*** (also discuss tomorrow)

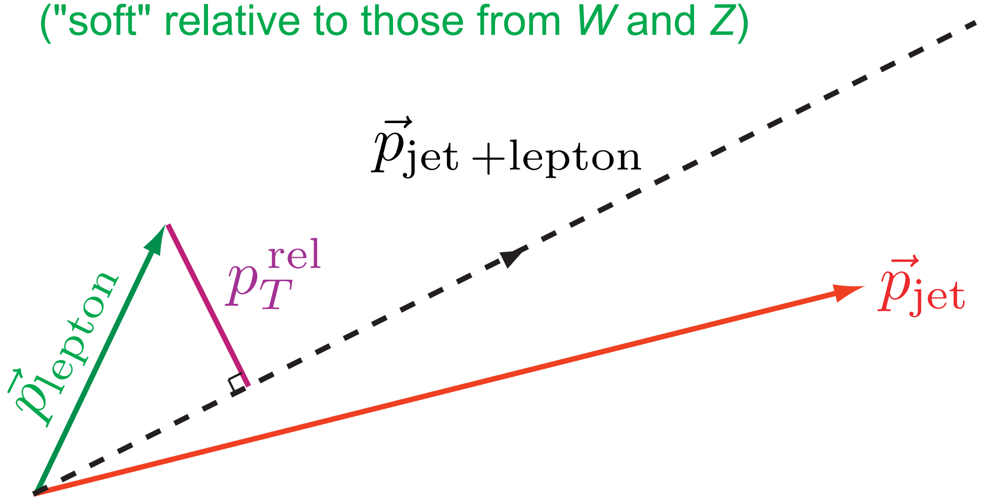


+several more

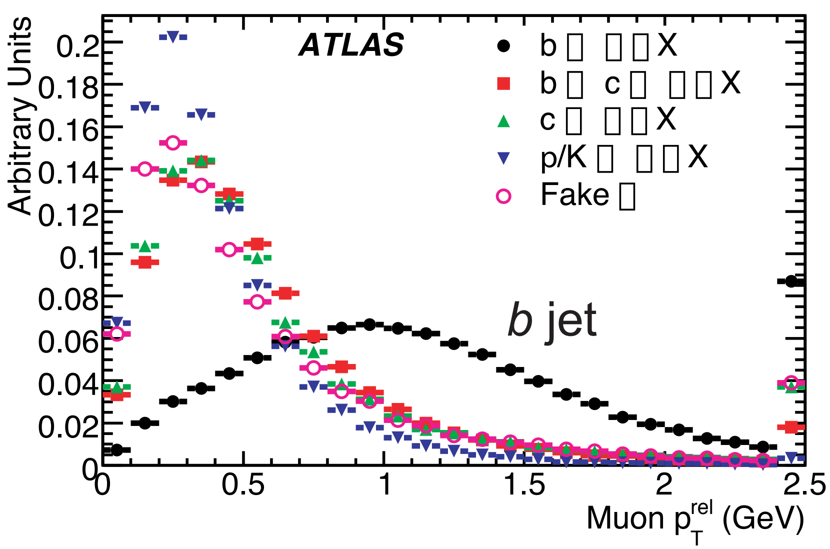
***b*-Jet Tagging**

"Soft muon" or "soft electron" tag

("soft" relative to those from *W* and *Z*)



Large transverse "kick" due to b mass



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- Large *b* quark mass

  Decay products have large p_T with respect to jet axis

  Large invariant mass of sec. vertex

- *b* hadron decays semileptonically

  $$b \rightarrow \ell,\ b \rightarrow c \rightarrow \ell$$

  ~10%

- Long *b*-hadron lifetime: $\langle L \rangle \approx 0.5 - 3.0\,\mathrm{mm}$

  Decay length Significance: L/σ_L

  How many tracks with large impact parameter significance: b/σ_b

  ...in 2-dim (*x*,*y*) or 3-dim

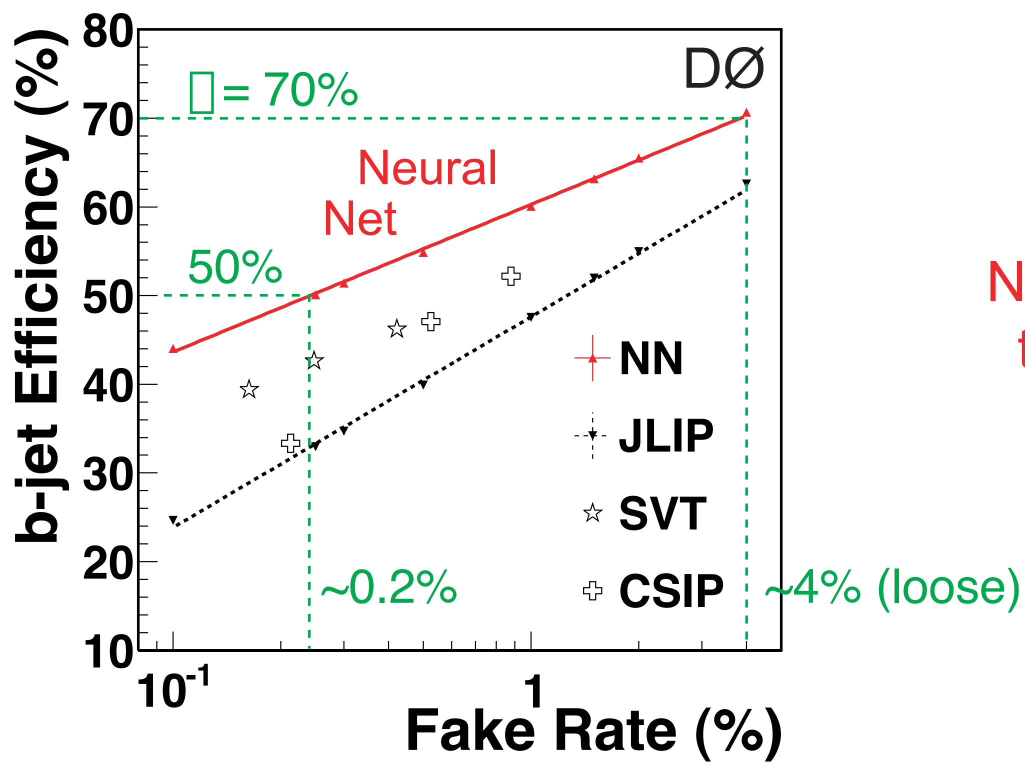
b-Jet Tagging

Efficiency from Data

Dijet events → $b\bar{b}$, approx. back to back → tag one side, test tagger on away side

More involved version, all in data:

- Two ***uncorrelated*** (lifetime, soft muon) taggers applied to both sides
- Two different samples with different *b*-jet fractions
- Solve 8 equations, 8 unknowns ("System 8")
- Check correlations, plus *check* with fits to MC p_T^{rel} distributions



Now back to top quarks...

b-Jet Tagging

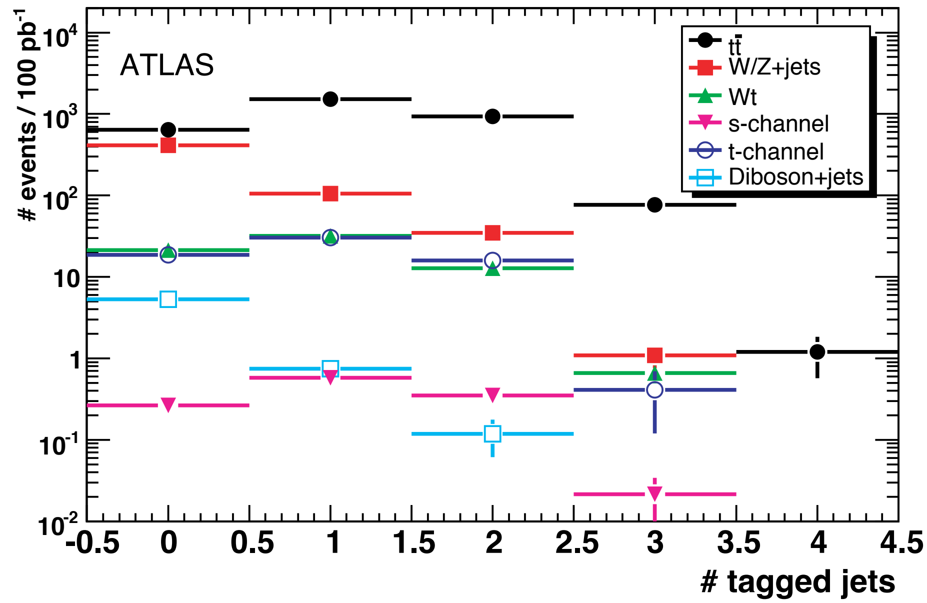
Efficiency from $t\bar{t}$ data @ LHC

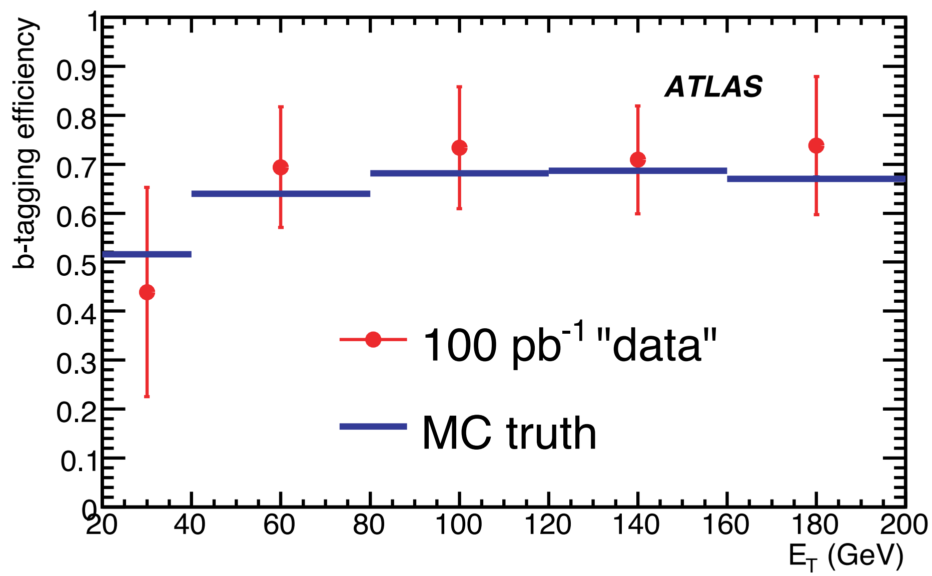
Higher-purity $t\,\bar{t}$ events at LHC;
"turn it around"

$$N_{(0\,\mathrm{tag})} \mathrel{\widetilde{\propto}} (1-\epsilon_b)^2$$
$$N_{(1\,\mathrm{tag})} \mathrel{\widetilde{\propto}} 2\epsilon_b(1-\epsilon_b)$$
$$N_{(2\,\mathrm{tag})} \mathrel{\widetilde{\propto}} 2\epsilon_b^2$$

Correct for backgrounds,
full likelihood fit (to the 3-tag as well...)

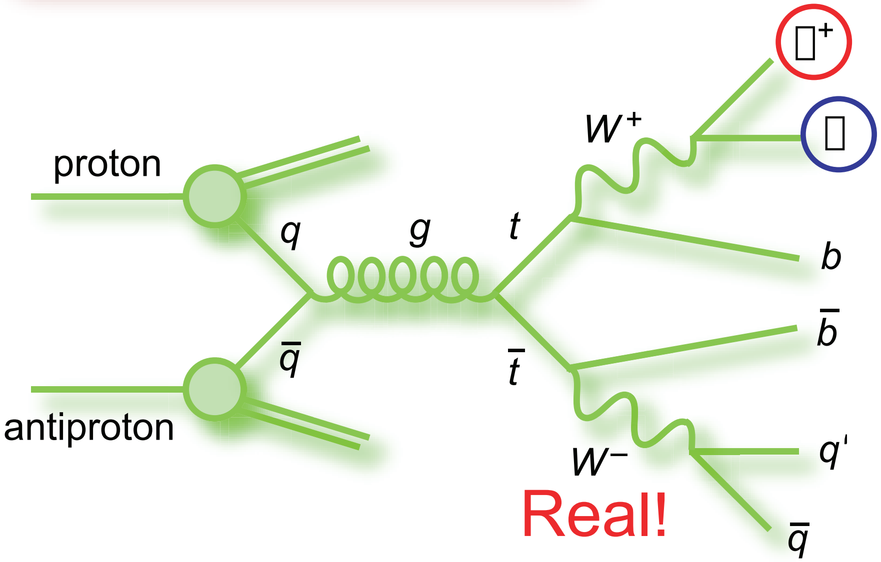
Overall precision to ~4% in 100 pb^{-1}





Top Quarks

...back to measuring top mass...



Require

isolated lepton + missing E_T + jets

- Needs excellent understanding of entire detector! Triggering, tracking, b-tags, electrons, muons, jets, $\not{E}_T$
- Performance must be understood and modelled well
- Dominant background will be W + jets (including W + 2 b-jets!)

Four quarks in the $t\,\bar{t}$ partonic final state

Require 4 jets?

No! Number partons   Number jets!

- More jets from
  gluon radiation from initial or final state
- Fewer jets from
  overlaps (merged in reconstruction)
  inefficiencies or cracks in detector
  fall outside □ acceptance or below p_T cut

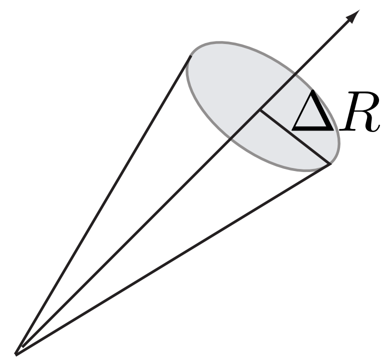
Jets/isolation aside →

ΔR Cones

- At hadron colliders often use □*R* as a measure of “distance” or separation in direction between particles

$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

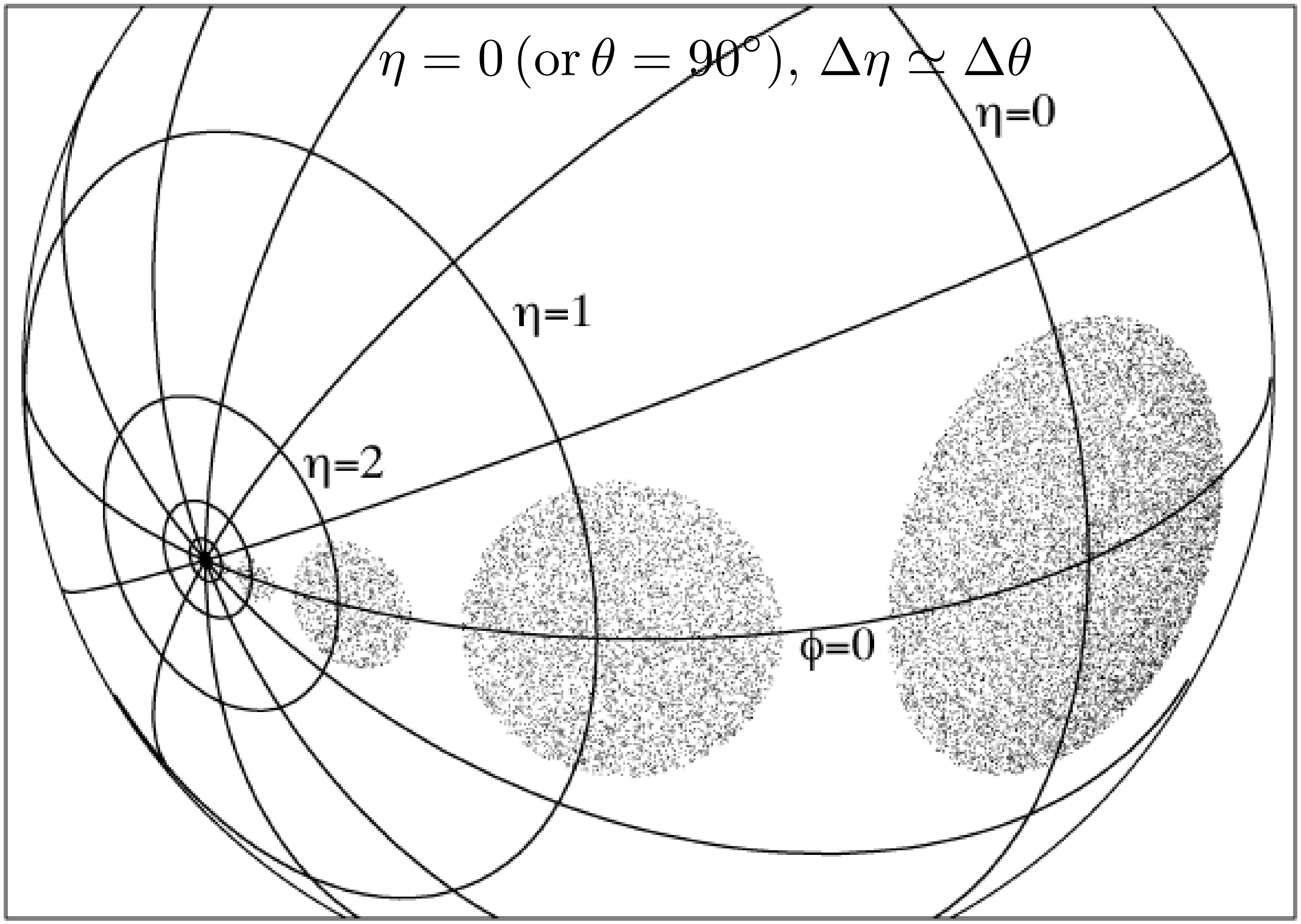
- Use “cones” in □*R* to associate particles with each other



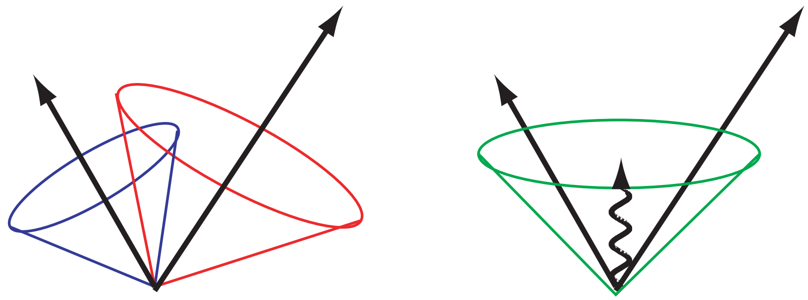
- Tend to think of these cones as circular and uniform, but they are not

ΔR Cones

- Typical applications:
  - Lepton isolation (like in top, $W \to e\nu$)
  - τ reconstruction, e.g., $\tau \to (n\,\mathrm{hadron})\,\nu$
  - Jet reconstruction, okay?



Jets

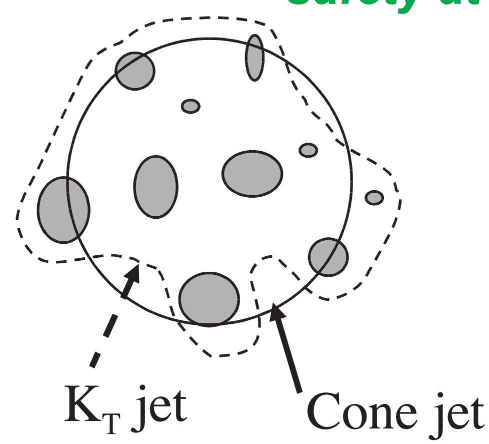


Old "Legacy Cone"

- Draw a □*R* cone around a seed
- Compute jet axis from E_T-weighted mean and jet E_T from sum
- Draw a new cone around the new jet axis and recalculate axis and new E_T
- Iterate until stable
- Algorithm is ***sensitive to soft radiation***

Tevatron Mid-Point Cone

- Use 4-vectors instead of E_T
- Add additional midpoint seeds between pairs of close jets
- Split/merge after stable protojets found ***improved infrared safety at NLO***



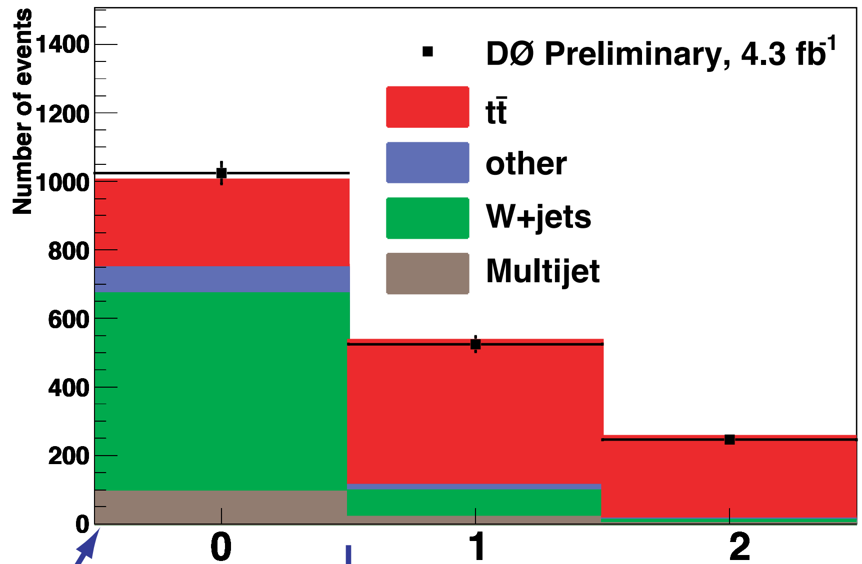
- K_T jets also infrared safe
- LHC: anti-K_T jets

Top Quarks

First, b-tag:

Since typical *b*-tagging efficiency ~50%, then for final state with two *b* jets,

Prob(2 tags) ~ 25%
Prob(1 tag) ~ 75%



Signal region

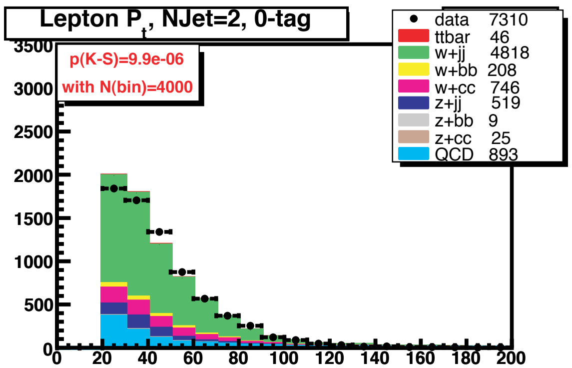
Control region
(particularly for lower N_{jet})
Verify background modeling

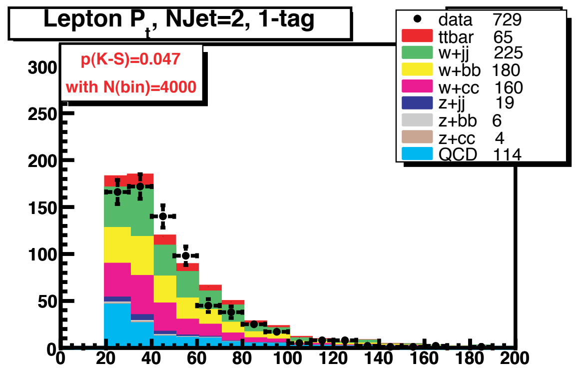
Top Quarks

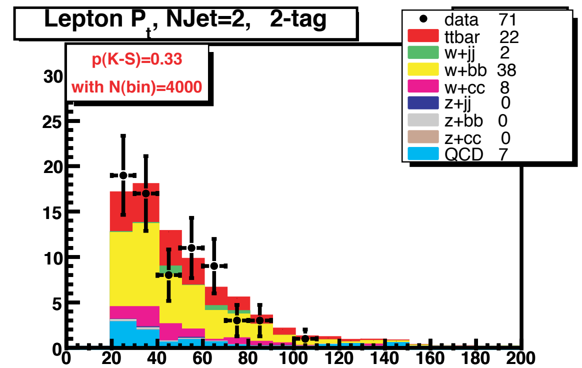
Understanding of backgrounds & assigning uncertainty

$0\,b - \text{jet tags}$ | $1\,b - \text{jet tags}$ | $2\,b - \text{jet tags}$

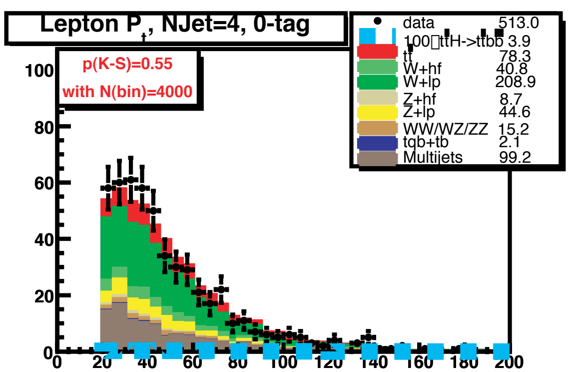
$N_{\text{jet}} = 2$

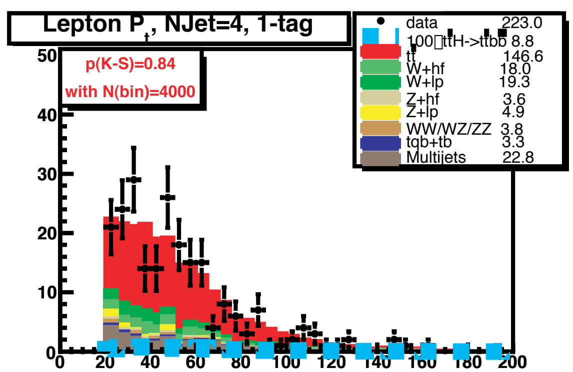


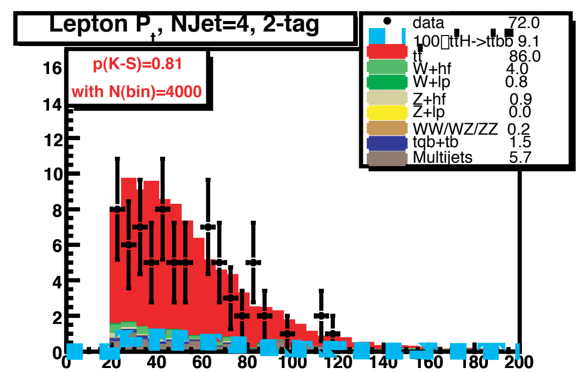




$N_{\text{jet}} = 4$







Top Quarks

Matrix Element Method for Mass

Construct probability density function as function of m_{top} for each event

$$P_{\text{sig}}(\vec{x}, m_{\text{top}}, JES) \propto \sum w_n \int_{q_1,q_2,\vec{y}} |\mathcal{M}(p\bar{p} \to t\bar{t} \to \vec{y})|^2 dq_1 dq_2 f(q_1) f(q_2) d\Phi_6 W(\vec{x}, \vec{y}, JES)$$

Weight that jet is a b-jet

Matrix Element (lepton + jets)

Parton PDF's

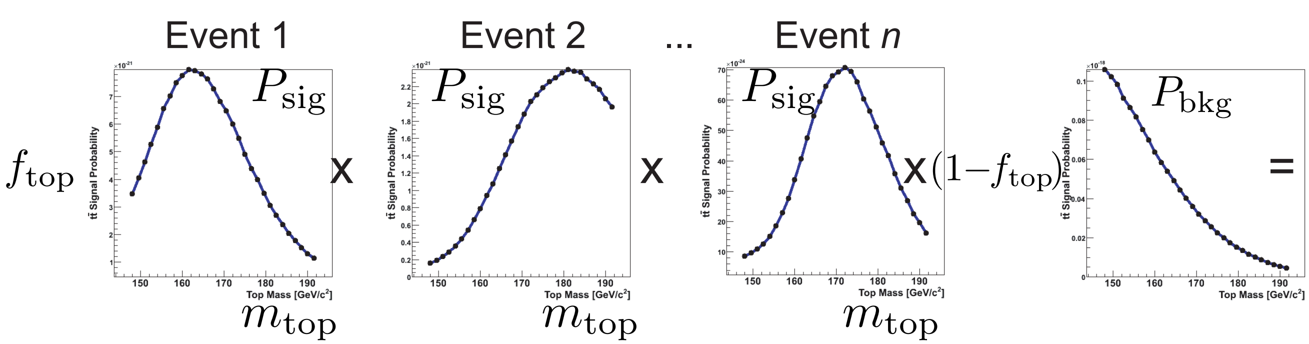
Observed kinematics (e.g., parton,lepton, neutrino 4-vectors) of event

Parton kinematics of event

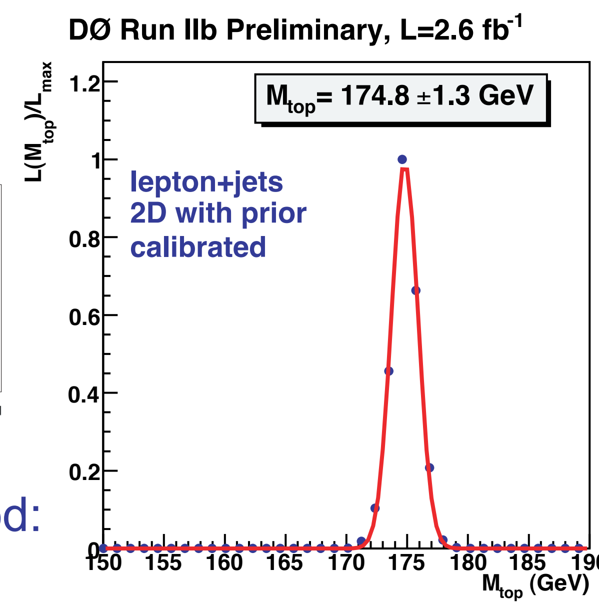
Transfer function

Calculating the probability for an event to be consistent with a *tt* decay for a given m_{top}

4-vectors with maximal topological information + correlations, maximal possible use of event info



Multiply probabilities for all the events for overal likelihood:



Top Quarks

Matrix Element Method for Mass

Construct probability density function as function of m_{top} for each event

Jet energy scale

$$P_{\rm sig}(\vec{x}, m_{\rm top}, JES) \propto \sum w_n \int_{q_1,q_2,\vec{y}} |\mathcal{M}(p\bar{p} \to t\bar{t} \to \vec{y})|^2 dq_1 dq_2 f(q_1) f(q_2) d\Phi_6 W(\vec{x}, \vec{y}, JES)$$

Matrix Element (lepton + jets)

Parton PDF's

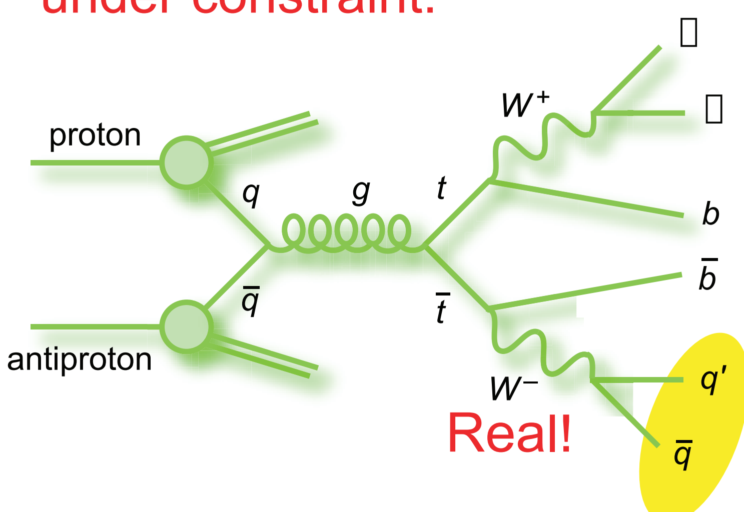
Observed kinematics (e.g., parton,lepton, neutrino 4-vectors) of event

Transfer function

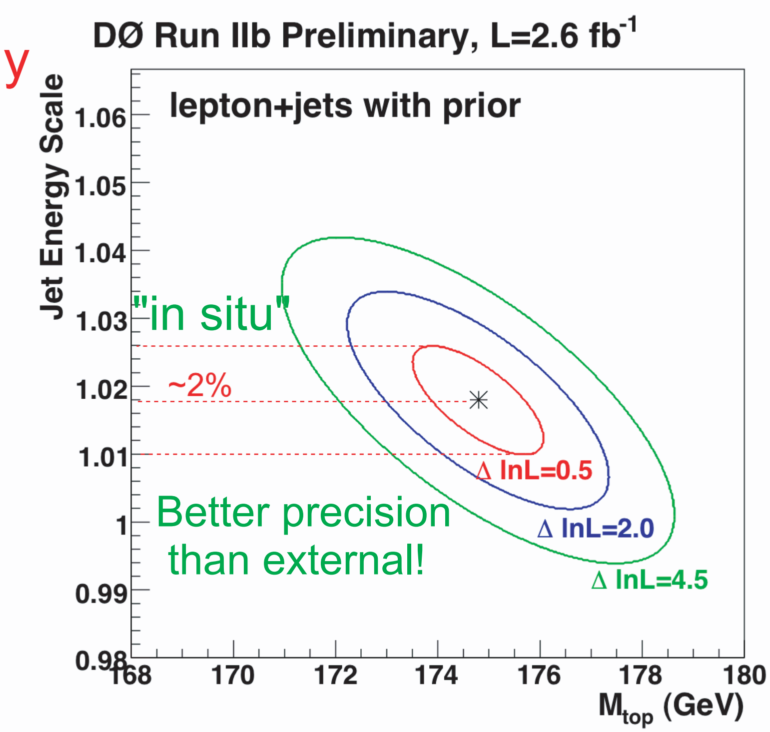
Parton kinematics of event

Weight that jet is a b-jet

Bonus! Knowledge of jet energy scale usually a dominantsystematic uncertainty – let float under constraint:



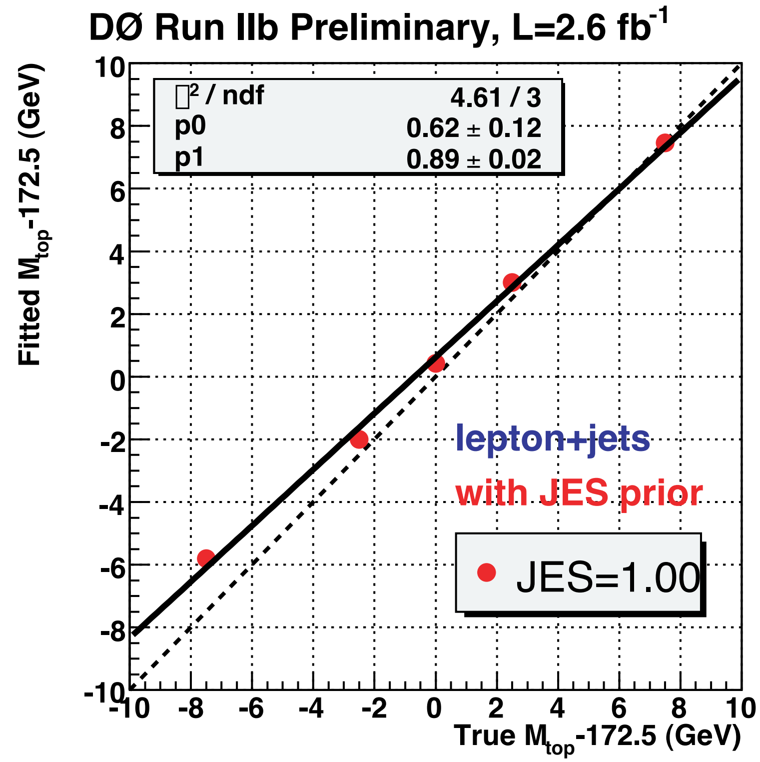
Constrain to M_W

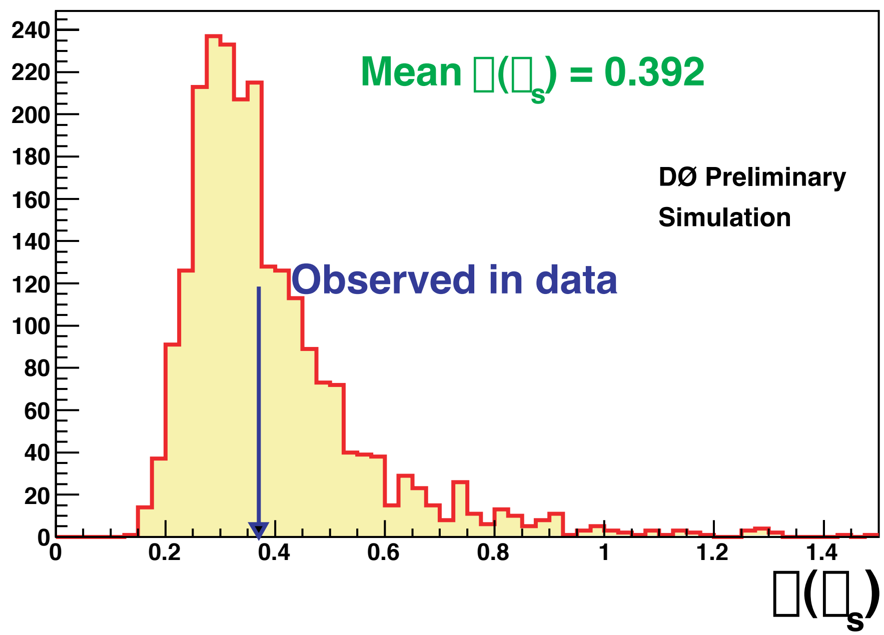


Top Quarks

Calibration/Check of analysis

The other essential role of MC
when measuring a property:
vary true value in MC, fit as if data:





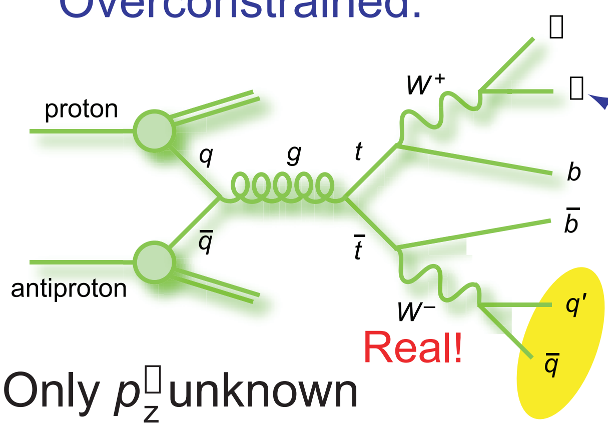
...and is fitted value and
its uncertainty consistent with
expectations? *Ensembles* of
MC events, statistics same as data
("luckiness")

Top Quarks

Template Method

- Identify variables $\vec{x}$ sensitive to parameter of interest (e.g., $m_{\rm top}$)

Overconstrained:



Only p_z^ν unknown

Constrain to M_W

$$\chi^2 = \sum_{\rm jets} \frac{(P_T^{i,\rm fit} - P_T^{i,\rm meas})^2}{\sigma_i^2} + \cdots \quad \text{Four vectors}$$

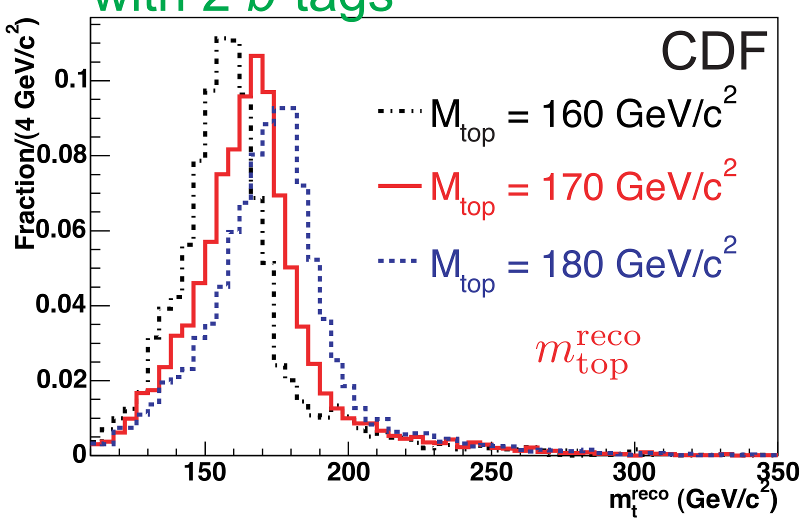
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2}$$

$$+ \frac{(M_{bjj} - m_{\rm top}^{\rm reco})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_{\rm top}^{\rm reco})^2}{\Gamma_t^2}$$

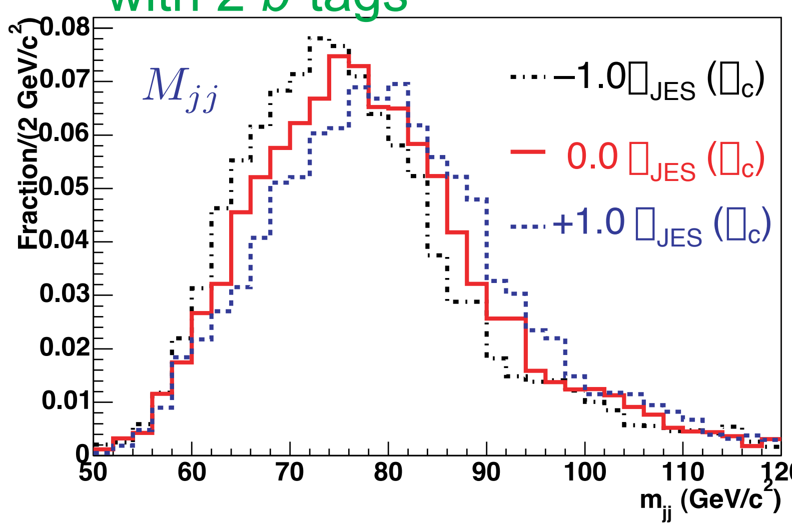
Minimize Each Event

- Using MC, generate signal distribution of $\vec{x}$ as a function of $m_{\rm top}$

with 2 *b*-tags



with 2 *b*-tags

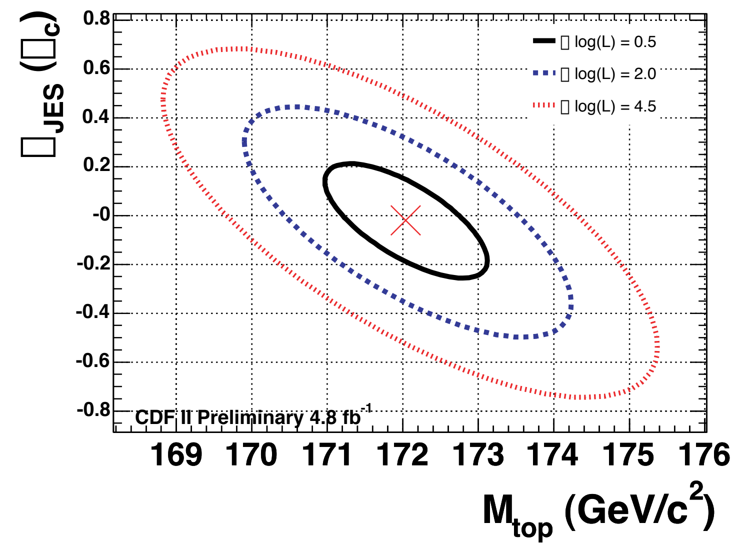


Top Quarks

Template Method

- Probability density functions for $m_{\text{top}}^{\text{reco}}$, M_{jj} for each point in a $(m_{\text{top}}, \Delta_{\text{JES}})$ grid using Kernel Density Estimate (KDE) approach
  → a non-parametric method for forming density estimates that can easily be generalized to more than one dimension

- Minimize likelihood of whole sample:



- Individual top quark mass measurements have a precision just under 1% → ***Hard!***
- Measurements with precision less than 0.1%? → ***Hardcore!***

W Mass

- A simple topology, but want crazy-good precision
- Use variables only in transverse plane

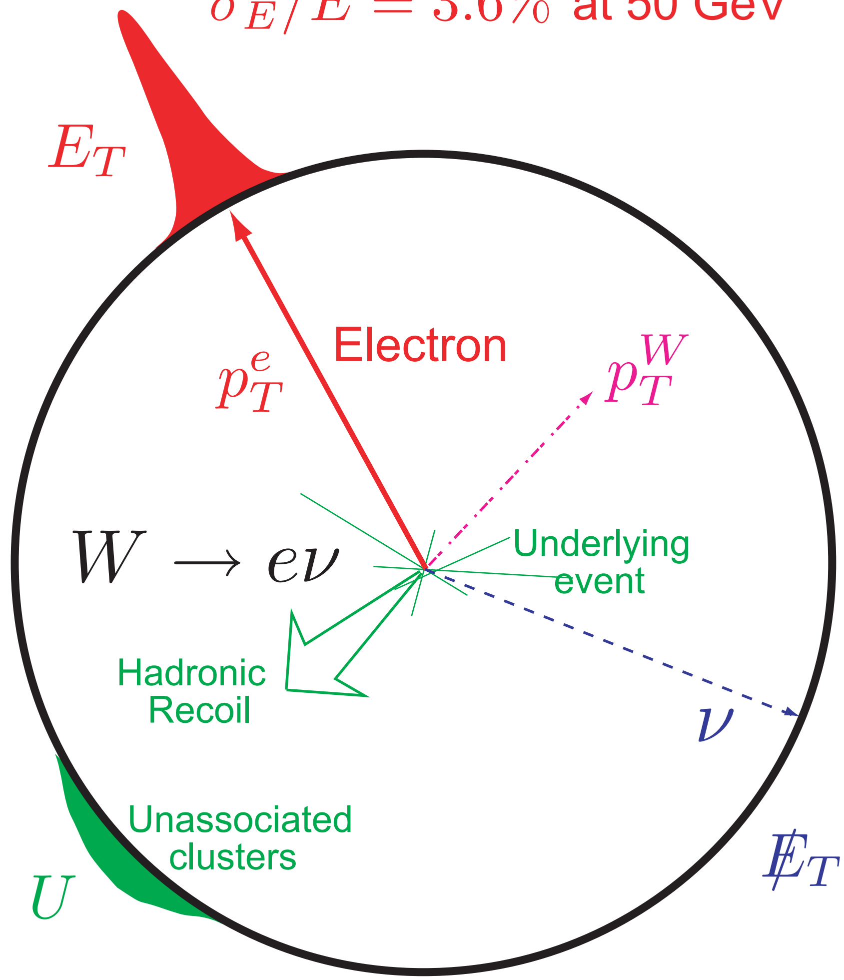
$$p_T^e \,, \not{E}_T \,, m_T$$

$$m_T = \sqrt{2 p_T^e E_T (1 - \cos \Delta\phi_{e-\nu})}$$

Less sensitive to knowledge of p_T^W (zero at LO; non-zero at NLO)

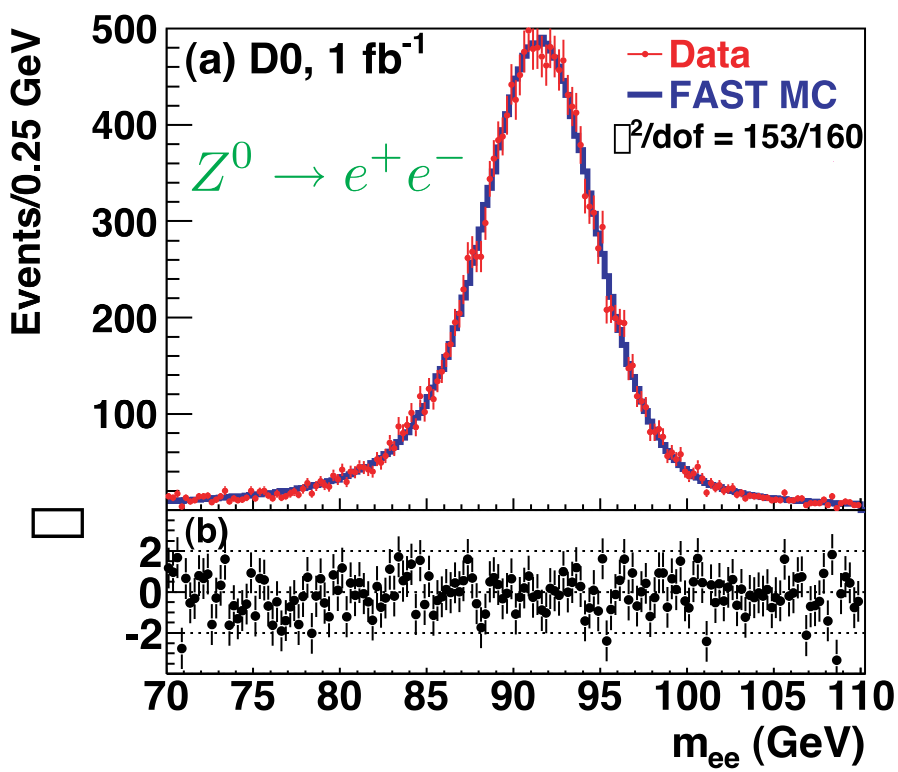
- Use knowledge of hadronic recoil through those unassociated clusters to make p_T^e and $\not{E}_T$ less sensitive to the transverse motion of the *W* boson

Electron energy resolution (□=0)
$\sigma_E/E = 3.6\%$ at 50 GeV



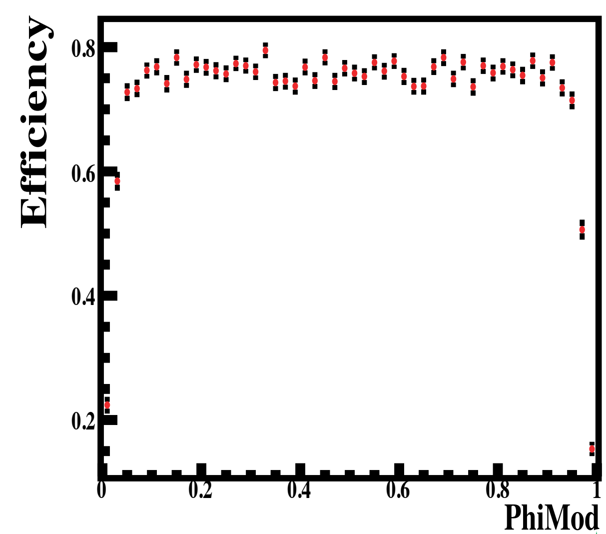
W Mass

- To get required precision, need many samples with statistics of ~10^8
  Precludes full MC, plus *doesn't get the details right at this level of precision.*
- Tune parametric ("fast") simulation using both full simulation and data; ultimately $Z^0 \to e^+e^-$ data control events



$$M_Z = 91.185 \pm 0.033\,(\text{stat})\,\text{GeV}$$
cf. $M_Z(\text{world average}) = 91.188\,\text{GeV}$

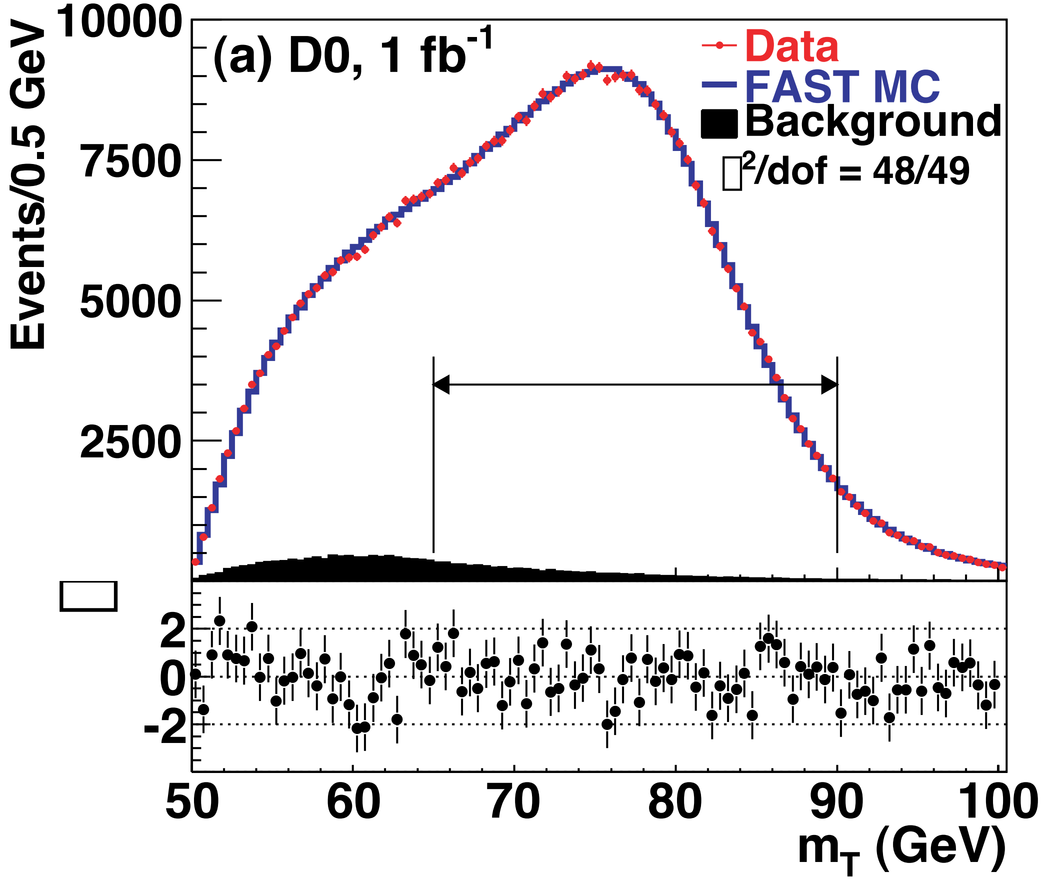
- Electromagnetic response and resolution in MC tuned using this sample (~400 templates, 50M events each)
- Only one of huge number of control plots



Few mm gaps between modules

W Mass

- Fit data to simulated distributions (templates in steps of $M(W)$ = 10 MeV) to determine mass



- Tested all methods with full MC simulation treated as data
- For data, blinded *W* mass value until control plots okay
- Also fit to p_T^e, $\not{E}_T$ and combine (not fully correlated!)

  The correlation coefficients are determined using ensembles of simulated events (other important use of MC).

W Mass

$$M_W = 80.401 \pm 0.021\,(\mathrm{stat}) \pm 0.038\,(\mathrm{syst})\ \mathrm{GeV}$$

- Most experimental systematic uncertainties limited by $Z^0 \to e^+e^-$ statistics; i.e., will improve with more data! (the importance of scales!)

TABLE II: Systematic uncertainties of the M_W measurement.

Source	M_W (MeV) m_T	p_T^e	$\not\!\!E_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron e ciencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

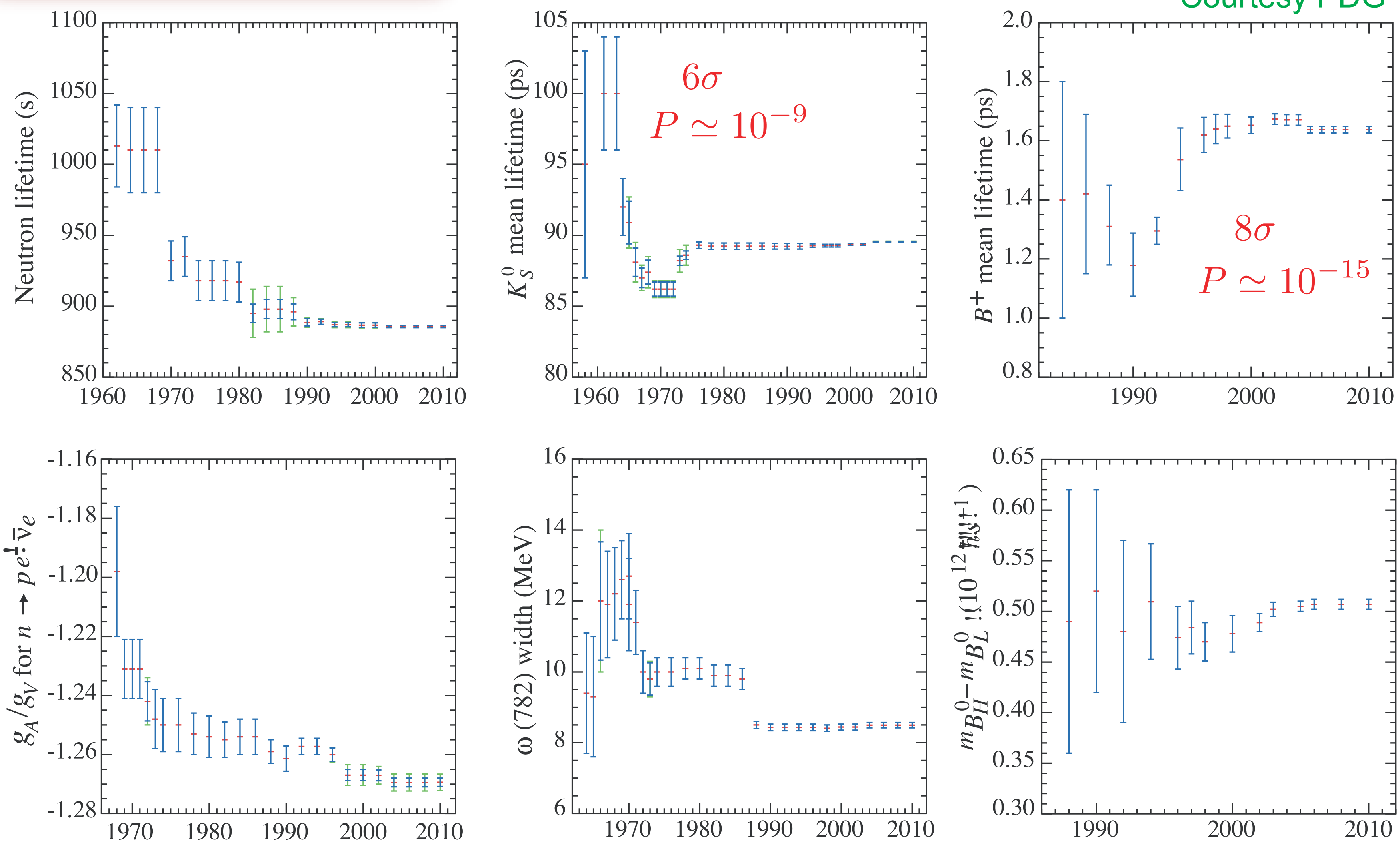
- 0.05% total precision: demonstrates what can be done working very hard with fundamentally straight-forward techniques ("fast" MC, templates)

(analysts should all receive "sub per mille medals")

Sobering...

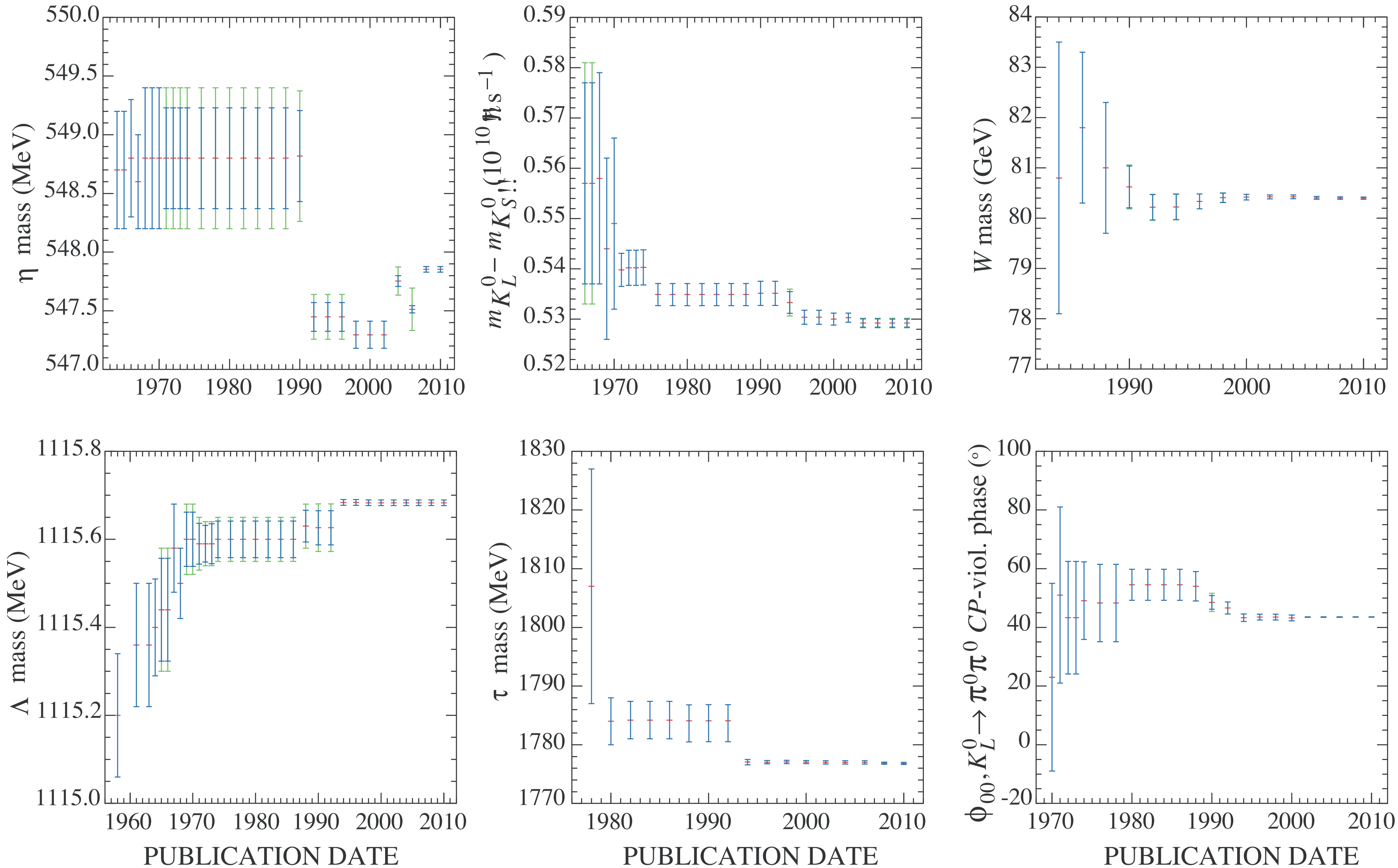
Particle physics' dirty little secret(s)

Courtesy PDG



Possible that the experimenters during a period paid too much attention to the level of agreement between their new result and the measurements of the recent past. If one judges whether a result is ready for publication by its agreement with the current world average, such disasters can happen!

...to be fair



η mass (MeV)
$m_{K_L^0} - m_{K_S^0}$ ($10^{10}\hbar$ s^{-1})
W mass (GeV)
Λ mass (MeV)
τ mass (MeV)
$\phi_{00}, K_L^0 \to \pi^0\pi^0$ CP-viol. phase (°)
PUBLICATION DATE
PUBLICATION DATE
PUBLICATION DATE

Biases

Unbiased if the expectation value of the estimator
is equal to the true value: $E[\hat{a}] = a$

Biased, doesn't matter how much statistics $E[\hat{a}] = a + \underbrace{b}_{\text{bias}}$

If the bias vanishes for large N, then the estimator is asymptotically unbiased

If we have mere statistical bias, this is usually not a problem and can be corrected!!
Experimenter bias occurs when human behaviour enters the equation.

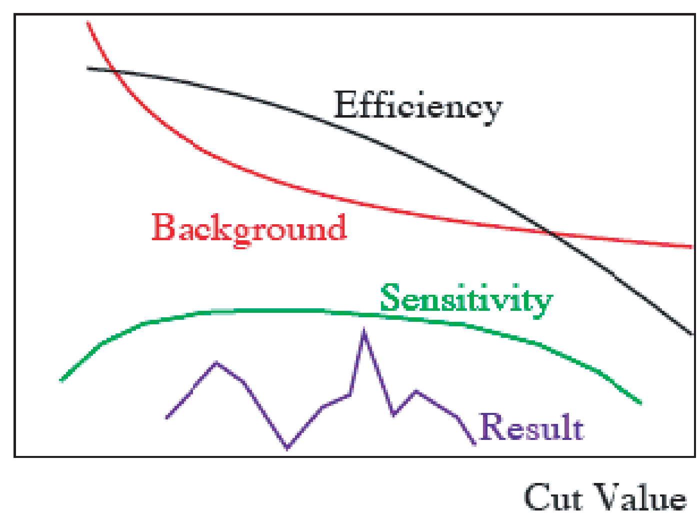
Biases

Typical Sources

Tuning on the data (a cardinal sin, particularly low stats)

- If you are not tuning on the data, why do you need to see the data, and what aspects do you need to see?
- e.g., making cut value choices within a reasonable range (e.g., plateau of sensitivity) but with a knowledge of the data

  A signal inside of 2500 events. Make 10 cuts, each 90% efficient, but 1% bias in each (i.e., upward fluctuation). Results in a 3σ effect in the resulting signal



Stopping when the data “looks right”

- A priori there is no inherent termination point of an analysis … try to set milestones before starting (easier said than done)

Biases

Typical Sources

- Looking for bugs when a result does not conform to expectation (and not looking when it does)
- Looking for additional sources of systematic uncertainty when a result does not conform
- Deciding whether to publish, or to wait for more data
- Choosing to drop "outliers" or “strange” events
- The data selection criteria are unconsciously adjusted to bring the answer closer to a theoretical value or a previously measured value.
- Comprehensive checks are performed if the answer disagrees with expectation, otherwise not so comprehensive. The extra checks might be invented by the analysts, or requested by convenors, editorial/review boardss, etc. (The experimenters feel more confident when the answer comes out “right”. These checks may lead to “corrections” that change the answer)
- Several competing analyses are performed using the same data. The responsibles charged with making the decision chooses which is worthy of publication after learning the answers, unconsciously favouring analyses that “come out right”.

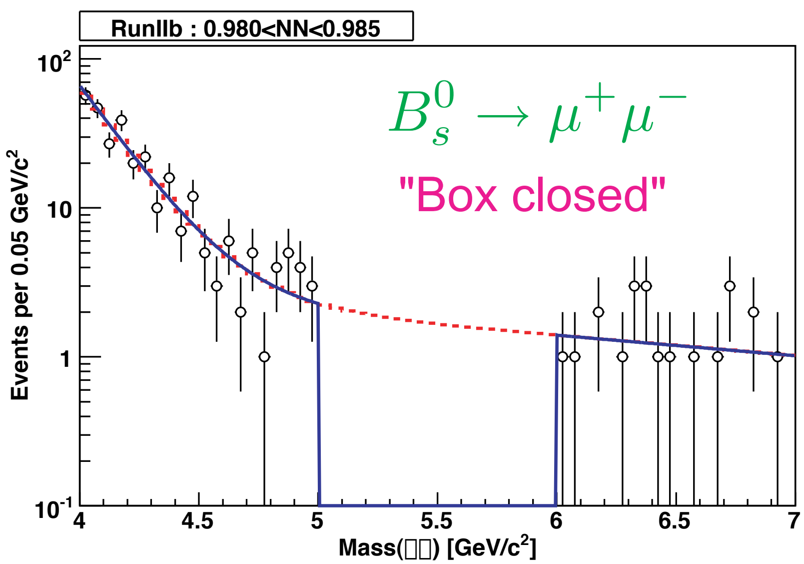
Biases

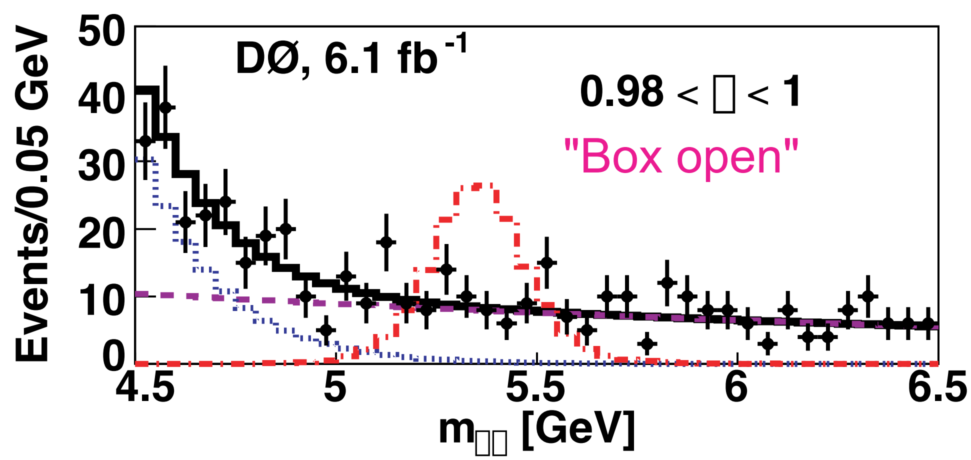
In each case, the experimenter bias is unintentional – the experimenters normally know that these practices are objectionable, but in each example, the course of the analysis is unconsciously influenced by their knowledge of how the outcome is affected

Blind Analysis

Know pitfalls and do best to avoid, or...

Hide the number of events (or don't look) in the signal region (i.e., the box) until the cuts have been finalized, the acceptance has been determined (with possible backgrounds estimated). At the final stage, the box is opened, and the answer (cross section measurement or limit) is computed.





Estimate background in blinded region by extrapolating from sidebands (for a certain neural net output bin)

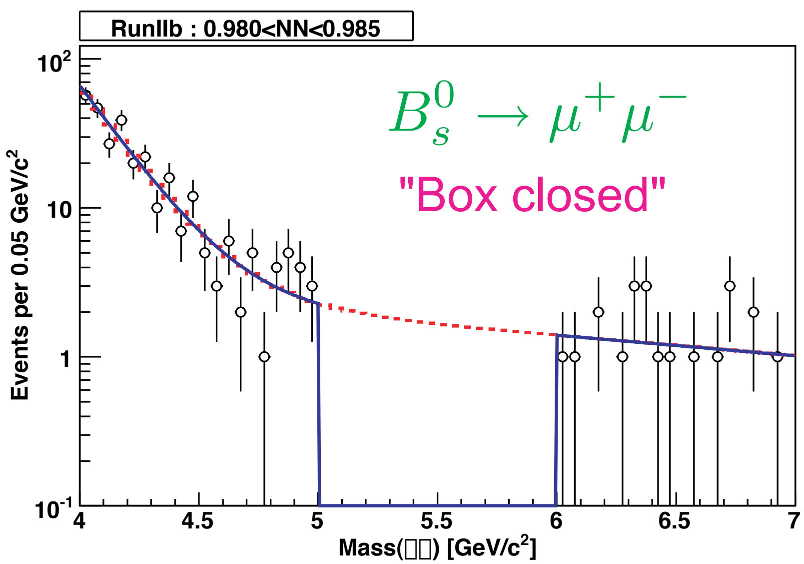
A priori decide on criteria/tests:

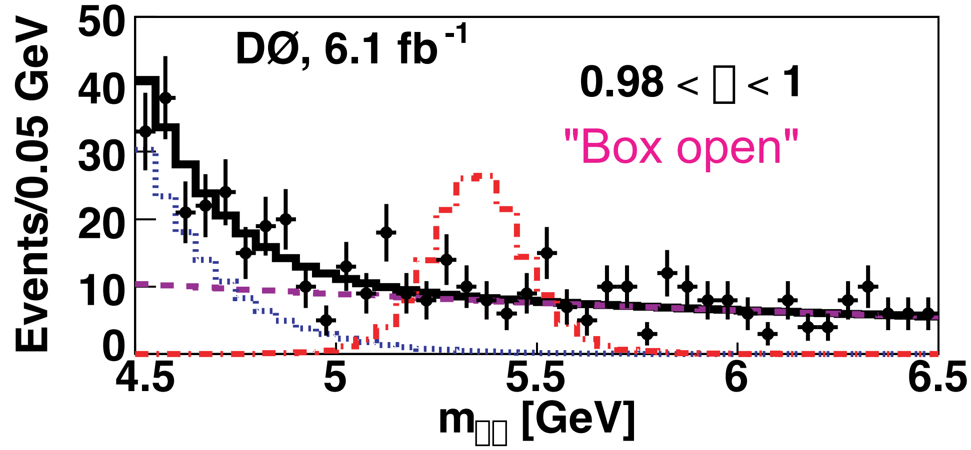
- For when to open box
- "Sanity" checks once box opened

Blind Analysis

Know pitfalls and do best to avoid, or...

Again, be "trigger aware", e.g., this one focusing on dimuon triggers significantly biased or "sculpted" the muon p_T spectrum, needing correction





Estimate background in blinded region by extrapolating from sidebands (for a certain neural net output bin)

A priori decide on criteria/tests:

- For when to open box
- "Sanity" checks once box opened

Blind Analysis

Know pitfalls and do best to avoid, or...

Shifting the answer ("Opening box" = revealing/removing shift) [exciting...]

- In some cases, it may be sufficient to shift the answer by adding a random (but fixed and unknown) offset □ to the answer.

- An advantage of this approach is that it allows two independent groups to analyze the same real data and compare their answers—both having the same random offset

e.g., KTeV:

$$\epsilon'/\epsilon\,(\mathrm{Hidden}) = \left\{ \begin{array}{c} 1 \\ -1 \end{array} \right\} \times \epsilon'/\epsilon + C$$

Shift constant C unknown, also +1 or –1 unknown (prevented KTeV from knowing which direction the result moved as changes were made)

(Similar for BaBar for sin2□)

e.g., $B_d^0 - \bar{B}_d^0,\ B_s^0 - \bar{B}_s^0$ oscillations. Randomize sign of flavor tag (B^0 or $\bar{B}^0$?). Should result in a null result (or apply to another system that should give a null result...)

Blind Analysis

Hiding (some) of the data!

- Might randomly split all data event-by-event into two sets: A and B.
  The analysis procedure is developed using set A – set B is not looked at all.
  Once the analysis algorithm is finalised, if, say, systematics limited,
  set A is discarded, and the analysis is run on set B, which determines the final answer (or used as an important control/confirmation check).
  (not always free of biases, e.g., calibration in A being used in B)

- Method seems suited to a case where many cut variations are tried on data in order to search for unanticipated signals (bump hunting being a prime example), but the analysis procedure is otherwise fixed.
  Since it is easy to be fooled by the statistical fluctuations that mimic new effects – if enough cut variations are investigated. In such cases, it is helpful to have the unexplored set B to confirm or refute any "discovery" in set A (or simply take more data...)

The fundamental strategy is to avoid knowing the answer until the analysis procedure has been set. Since checks may lead to a change (or correction) of the procedure, they should be completed, or at least scheduled, before the answer is revealed.